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Advancing Aeronautics

A Decision Framework for Selecting Research Agendas

Philip S. Antón, Liisa Ecola, James G. Kallimani, Thomas Light,
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Sponsored by the National Aeronautics and Space Administration



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Preface

A significant amount of the dramatic progress made in the United States aviation industry during its first century was the result of publicly funded research. This ranged from foundational research on airfoils, sponsored by the National Advisory Committee for Aeronautics, to support for development of the most complicated air traffic control system in the world. As the industry enters its second century, it stands at a crossroads. Public funding for aeronautics research has been static or decreasing in recent years, raising questions of what should be funded and why.

The United States needs a consistent vision of where aeronautics could take the nation and a framework to help policymakers prioritize potential projects given fiscal realities. Recent proposals, including the useful National Research Council's Decadal Survey of the aviation industry, have attempted to provide such a vision, but they often provide a technical perspective based on specific, narrow technical opportunities from current research and new ideas, not a strategic vision of the greatest challenges, governmental role, social needs, potential payoffs, economic drivers, etc. Most also lacked a comprehensive and objective prioritization framework for helping policymakers make programmatic decisions and tradeoffs.

Recognizing the need for such a framework, the National Aeronautics and Space Administration's (NASA) Aeronautics Research Mission Directorate asked the RAND Corporation to assess what is required to develop a strategic view of aeronautics opportunities and to outline a framework by which to evaluate the nation's future requirements for aeronautics research. This monograph is the final report on that research, which was conducted primarily between April 2007 and June 2009. It should be of interest to NASA, the Office of Science and Technology Policy, the Department of Defense, the Federal Aviation Administration, the Office of Management and Budget, congressional decisionmakers, and the aerospace industry.

The research reported on in this monograph was funded by NASA Headquarters. The study was conducted jointly under the auspices of the RAND Transportation, Space, and Technology (RAND TST) Program within RAND Infrastructure, Safety, and Environment (ISE); and the Acquisition and Technology Policy Center of the RAND National Security Research Division (NSRD).

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The RAND Acquisition and Technology Policy Center

This research was jointly conducted within the Acquisition and Technology Policy Center of NSRD. NSRD conducts research and analysis for the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the defense agencies, the Department of the Navy, the Marine Corps, the U.S. Coast Guard, the U.S. Intelligence Community, allied foreign governments, and foundations.

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Summary

Publicly funded research has long played a role in the development of aeronautics, ranging from foundational research on airfoils to development of the air-traffic control system. Yet more than a century after the research and development of successful controlled, sustained, heavier-than-air flight vehicles, there are questions over the future of aeronautics research. The field of aeronautics is relatively mature, technological developments within it have become more evolutionary, and funding decisions are sometimes motivated by the continued pursuit of these evolutionary research tracks rather than by larger factors. These developments raise questions over whether public funding of aeronautics research continues to be appropriate or necessary and at what levels. Tightened federal budgets and increasing calls to address other public demands make these questions sharper still.

To help it address the questions of appropriate directions for publicly funded aeronautics research, the National Aeronautics and Space Administration's (NASA's) Aeronautics Research Mission Directorate (ARMD) asked the RAND Corporation to assess the elements required to develop a strategic view of aeronautics research opportunities; identify candidate aeronautic grand challenges, paradigms, and concepts; outline a framework for evaluating them; and exercise the framework as an example of how to use it. Accordingly, this research seeks to address these questions:

- What aeronautics research should be supported by the U.S. government?
- What compelling and desirable benefits drive government-supported research?
- How should the government—especially NASA—make decisions about which research to support?

Advancing aeronautics involves broad policy and decisionmaking challenges. Decisions involve tradeoffs among competing perspectives, uncertainties, and informed judgment. We examine these challenges and develop a unifying decision-making approach that balances perspectives, simplifies decisionmaking processes, and enables strategic thinking and explanation of the resulting decisions. Our research also provides some aeronautics research options and opportunities for the United States

along with underlying data and analysis to show how decisionmakers could use this approach to create and refine research-investment portfolios.

What Aeronautics Research Should Be Supported by the U.S. Government?

Publicly supported research should focus on areas of public good that lack incentives for private-sector investors. In economic terms, it should focus on areas where the net present value (NPV) or benefit-cost ratio (BCR) is high and positive, yet where the NPV would be negative for private investors. Government research should provide a public good, not subsidize private-sector activity.

Policymakers can use available data to estimate the monetized benefits and costs for possible research projects. Such estimates should consider the demands for the benefits of research and the technical and other challenges to conducting it. They should consider not only the costs and benefits of a given research project but also of anticipated subsequent projects. Figure S.1 provides an overview of how to consider whether a research project should receive public or private funding, from identifying uses of the project to estimating the NPV of the research.

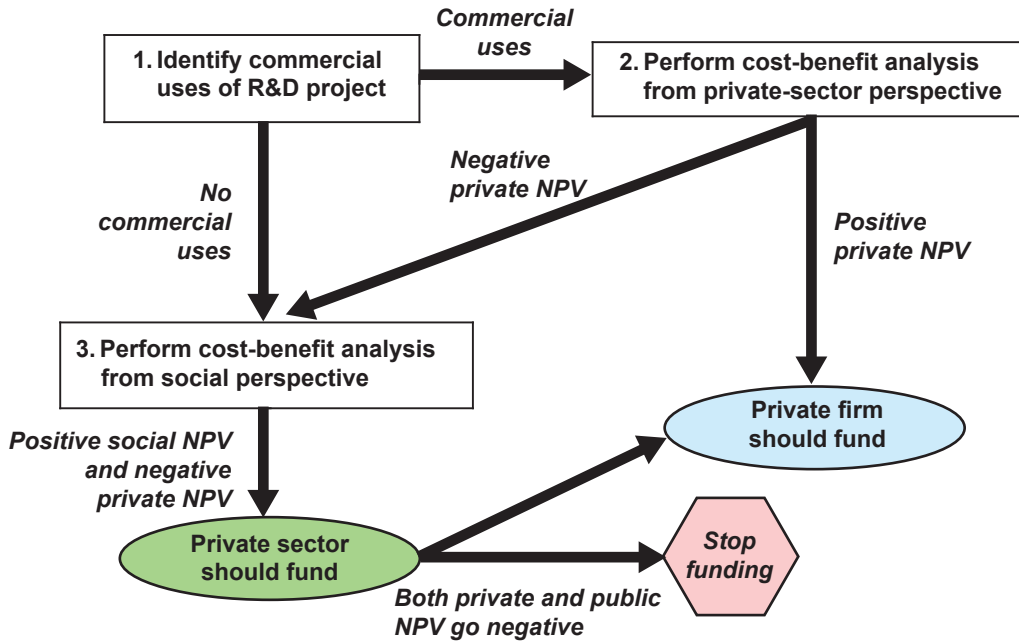
Estimates of the costs and benefits of research might be only rough approximations. Nevertheless, they can convey a sense of the magnitude of the possible benefits from research as well as of the full range of costs over time that may be required to reap those benefits. We emphasize not precision but gathering and conveying a sense of the magnitude of research costs and benefits, with benefits and costs distributed over time discounted to a common unit of measurement.

What Compelling and Desirable Benefits Drive Government-Supported Research?

Appropriate topics for publicly supported research may number in the hundreds and cut across multiple broad national goals such as safety, efficiency, capacity, flexibility, comfort, competitiveness, reducing environmental effects and travel time, and supporting space exploration and national defense. Integrating such multiple dimensions is key to research decisionmaking.

Figure S.2 illustrates key dimensions that can inform identification and prioritization of aeronautics research options. These are national policies and plans, grand challenges or “visions” for aeronautics, technology, and social benefits or “drivers,” which can act independently or reinforce each other. For example, technology can enable new visions and application concepts that, in turn, generate social demands for such applications. Policies and plans can set new directions as goals and visions or

Figure S.1
Langford-GRA Model of Public Sector Research and Development Prioritization



SOURCE: Vonortas and Hertzfeld (1998).

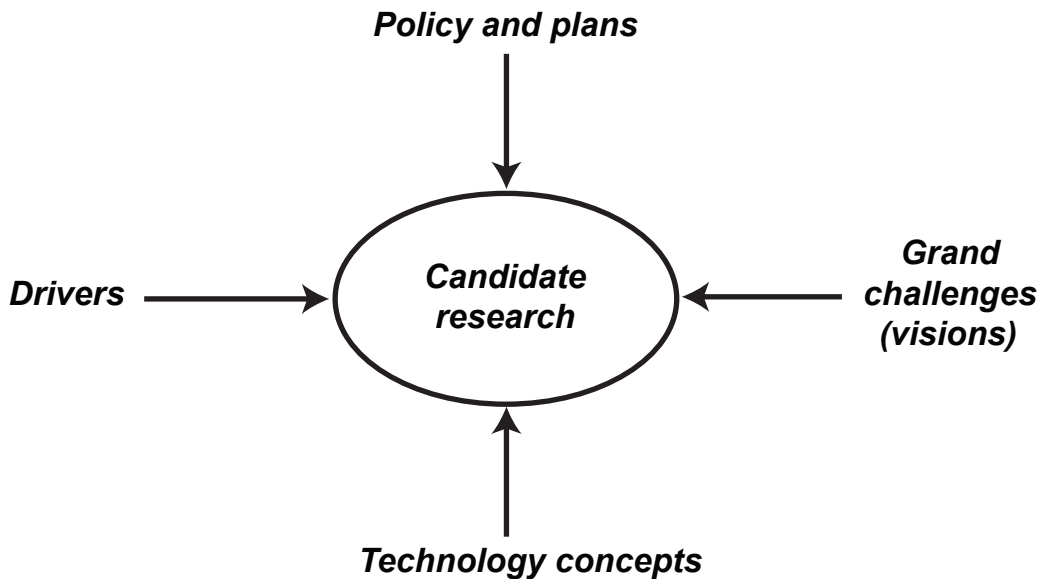
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can reinforce the importance of competing social demands resulting from technology-enabled application concepts. Many proposals have considered only one or two of these dimensions, resulting in less-than-compelling arguments for the proposals specifically and aeronautics research generally. In particular, analysis and discussion of social and economic drivers for aeronautics research has been lacking.

Policy and Plans

U.S. policy for aeronautics research is evolving and does not dictate specific directions. It limits aeronautics research to areas that do not support a single company or to areas that industry cannot fund. The policy frames the research portfolio, reaffirming, for example, the broad role NASA should play, rather than specifying it. Periodic national research and development plans are more detailed than the policy but do not direct activities for specific agencies and do not preclude other research activities. Government agencies and departments still conduct their own research planning according to their specific missions in combination with the national policy and plans. In sum, the policy and plans serve a useful coordinating and communication function but, by themselves, do not direct research or dictate research investment decisions and tradeoffs.

Figure S.2
Dimensions That May Inform Aeronautics Research Options



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Social and Economic Drivers for Research

Existing data indicate several social and economic challenges that aeronautics research can address—as well as areas where aeronautics research needs may need to be traded off against others. These include

- airspace throughput demands that are forecast to increase 50 percent by 2025, overwhelming current capacity
- flying remotely piloted vehicles in U.S. airspace for military and civil purposes
- airline delays, primarily from weather and airport terminal congestion, costing U.S. society about \$40 billion annually
- commercial air carrier fatalities resulting in an annual cost from loss of life of \$90 million in commercial aviation—and of \$3 billion in general aviation (or all aviation excepting military and scheduled commercial)
- life-cycle safety of new composite materials and structures
- social cost of carbon dioxide emissions totaling \$3 billion annually—a substantial sum but a level only about one-fifth that for automobiles, which policymakers might prefer to address as an alternative to aeronautics research¹

¹ When considering investments in aeronautics research, comparisons with similar social demands in other domains help provide perspective on the relative importance of that research. Thus, examining the relative magnitude of a problem such as emissions in aeronautics and other domains (such as automobiles) can help decision-

- nitrogen oxide emissions, which, while also substantial, are, on a per-passenger mile level, only one-tenth that of automobiles—another topic that policymakers may prefer to address.

In short, although there are several areas of aeronautics challenges worthy of public investment, some, such as emissions, may not be as pressing in aeronautics as they are in other fields, such as automobile travel, and others, such as fatalities, may be more pressing in some areas of aeronautics than others.

Grand Challenges

To help identify appropriate directions for future research and possible projects to support them, we suggest grand challenges to unify different research goals and inspire research. Table S.1 illustrates several possible grand challenges by principal policy areas.

Grand challenges can help identify multiple research possibilities addressing a broad, common goal. Consider, for example, research to reduce travel time. Travelers are willing to spend only about \$20 to \$40 per hour to recoup time otherwise lost to travel. It also appears that non-aeronautics-related delays (e.g., traffic delays in driving to airports, security check-in delays at airports) are much larger concerns than trying to increase travel speed to supersonic levels. A grand challenge related to supersonic travel, therefore, would do well to reflect practical realities by targeting prices comparable to current transonic jet flights while mitigating noise and emission concerns.

Grand challenges should reflect needs, costs, and technical reality. The magnitude of a need, its value, competing social and economic drivers, technical realities, and those benefiting from resulting research should all be considered in considering these visions.

Technology

Policies and plans, grand challenges or visions, and social and economic drivers of research must be tempered by technical realities. Decisionmakers should align research ideas and opportunities with available or feasible technologies. This can ensure practical results, sufficient budgets, complementary advances, and justifiable programs. Otherwise, research may be conducted for its own sake or toward applications with diminishing returns.

Table S.1
Illustrative Aeronautics Grand Challenges and Themes

Policy Principal Areas	Possible Grand Challenge
Safety	Maintain passenger safety levels as the industry moves from aluminum to composite airplanes
	Make general aviation as safe as commercial passenger air travel
Environment	Planes as fuel efficient as trains
	“Silent” airplane
	Zero greenhouse-gas emission plane (hydrogen plane?)
Airspace	Triple passenger air transport system throughput
	Unmanned vehicles in U.S. civil airspace
Reduced travel time	Green, quiet, supersonic flight at transonic prices
Increased travel comfort	<i>(none—problem not dominated by technology)</i>
Convenience	Safe personal air vehicles
Space access	Practical air-breathing space-access vehicles
National security	Month-long (or even year-long) loitering surveillance aircraft
	Automated unmanned aircraft
	Hypersonic global-strike vehicle
	Unmanned vehicles in U.S. civil airspace
	Cost-effective military vertical envelopment transport vehicles

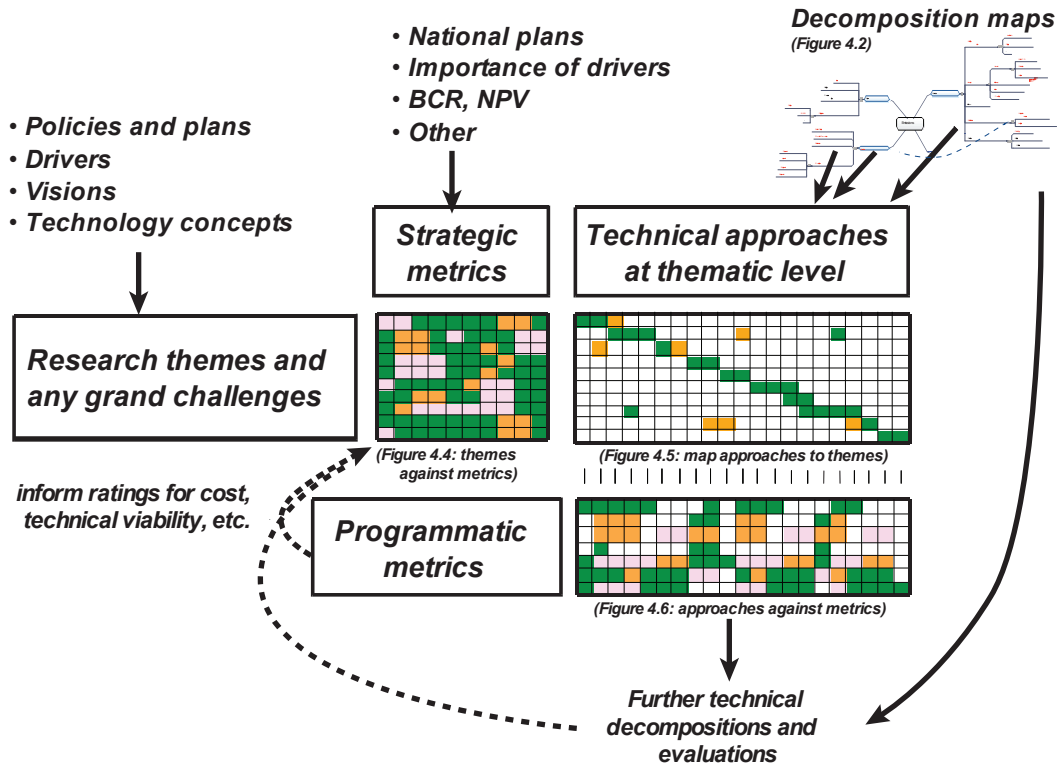
NOTES: Vertical envelopment is a “tactical maneuver in which troops, either air-dropped or air-landed, attack the rear and flanks of a force, in effect cutting off or encircling the force” (DoD, 2010). See, for example, Grossman et al. (2003) for a discussion of this concept and its technical and logistical challenges.

How Should the Government—Especially NASA—Make Decisions About Which Research to Support?

Our decision framework, illustrated in Figure S.3, integrates multiple perspectives in a process that uses groups of objective metrics to set priorities among competing research options. To illustrate how to use the framework, we provide in the monograph specific examples of our analysis and data collection along each of the following steps in exercising the framework.

It begins in the upper left corner of the figure, with a grouping of candidate research ideas we extract or develop from policy and plans, social and economic drivers, technology, and grand challenges. Such grouping will require many steps. The resulting broader research themes will facilitate debate and consideration of research

Figure S.3
Hierarchical Decision Framework Components for Prioritizing Research Themes, Grand Challenges, and Technical Approaches



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directions. The scope and number of research themes is key to the effectiveness of the decision framework. Too narrow and many, and the process becomes unwieldy. Too broad and few, and it becomes difficult to identify lower-priority areas. The research themes also need to be understandable to non-technical policymakers and the public to facilitate prioritization discussions and transparency.

These research themes should then be evaluated against strategic metrics (top center of Figure S.3; see also Figure 4.4). Using metrics allows decisionmakers to rate options objectively against varying interests and to see the tradeoffs between them. In the monograph, we review priorities in national plans, measures of the value of drivers (e.g., the economic cost of pollution), economic metrics such as BCR and NPV, and other measures to generate a list of potential strategic metrics for evaluating the research themes. A matrix showing the ratings of options against strategic metrics allows the decisionmaker to easily see how each project compares with metrics reflecting their priorities. Metrics should not only reflect policies and plans, social and economic drivers, visions for aeronautics research, and technology but also cost, benefit, and value metrics such as NPV and BCR. For illustration purposes, we show in the

monograph notional values in the matrices to demonstrate how the framework would work. More specific values should be informed by an exercise that obtains evaluations and judgments by domain experts in the relevant research fields.

The process also evaluates technical approaches to addressing research themes and grand challenges (upper-right corner of Figure S.3; see also Figure 4.5). Many of these may emanate from our decomposition of grand challenges into technical approaches (upper-right corner of Figure S.3; see also Figure 4.2), employing our decompositional maps that show the logical approaches that could be taken to address different research themes at the thematic and programmatic levels. Such decompositions also help identify technical approaches that can address multiple grand challenges.

The framework also includes a step for assessing technical approaches against program metrics (bottom right of Figure S.3; see also Figure 4.6). This prioritization provides more detail on the viability of pursuing a research theme and therefore informs the evaluation of research themes and grand challenges against strategic metrics. Again, the monograph includes notional values for such matrices to illustrate how the framework would work, but domain experts should be consulted in an exercise to obtain evaluations and judgments.

The goal of this process is to explain research decisions to oversight bodies, Congress, and the public. Showing all options, and the processes used to choose among them, helps others better understand the decisions made while also conveying information, such as the sufficiency of budgets relative to needs, and enables dialogue on priorities. Showing matrices as well, although more complicated than merely listing research to be funded, allows others to understand whether there is valuable research that cannot be funded under current budgets or whether research is approaching diminishing returns.

Conclusions

Aeronautics is a relatively mature field struggling to find revolutionary yet practical designs and concepts. Still, social and economic “drivers” for aeronautics research remain. Our framework can inform the creation of new programs and the refinement of existing ones.

In our initial exercise of reviewing and analyzing relevant inputs and pilot-testing the framework, we found that such a decision framework can lead to large, compelling rationales and technical ideas for advancing aeronautics. Our exercises found some interesting candidates as well as some objectives and concepts that are less compelling when compared with practical realities, alternative problems with easier solutions, and the benefits of the research. More analysis and participation in the framework process by the relevant stakeholders is needed. However, our initial work shows that the application of this model in government decisionmaking is likely to lead to further refinement in which new questions and preferences will emerge.

NASA's ARMD should consider adopting and adapting these approaches both in planning and explaining its research program. These approaches can give decisionmakers and the public a better understanding of the challenges facing aeronautics and how well the government's budget can address them.

Policymakers—rather than merely choosing among a list of technical ideas and opportunities proposed by researchers—should explicitly analyze social and economic drivers of research; the full extent of research, development, and implementation costs; and the resulting benefits—all tempered by technical realities. The integration of these multiple perspectives will result in more persuasive research plans. Without it, aeronautics research may become exploratory endeavors with unclear ties to results and drivers—or, worse yet, a collection of insufficiently funded activities that is unlikely to benefit society.

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The authors, of course, reserve responsibility for any errors that remain in this document.

Abbreviations

ARMD	Aeronautics Research Mission Directorate
ASEB	Aeronautics and Space Engineering Board
ASME	American Society of Mechanical Engineers
ATA	Air Transport Association
ATM	air traffic management
ATP	Aeronautics Test Program
BCR	benefit-cost ratio
BTS	Bureau of Transportation Statistics
BTU	British thermal unit
BWB	blended-wing body
CAEP	Committee on Aviation Environmental Protection
CBRNE	chemical, biological, radiological, nuclear, and explosives
cd	coefficient of drag
CFD	computational fluid dynamics
CH ₄	methane
CM&O	Center Maintenance and Operations
CO	carbon monoxide
CO ₂	carbon dioxide
DARPA	Defense Advanced Research Projects Agency
dB	decibel

DNL	day-night average A-weighted sound level
DoD	Department of Defense
DOT	Department of Transportation
DSB	Defense Science Board
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ESTOL	extremely short takeoff and landing
EU	European Union
FAA	Federal Aviation Administration
FTE	full-time equivalent
FY	fiscal year
GAO	Government Accountability Office
GPS	global positioning system
H	high
H ₂ O	water
HoQ	House of Quality
HWB	hybrid-wing body
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
ISE	Infrastructure, Safety, and Environment
ISR	intelligence, surveillance, and reconnaissance
IVHM	integrated vehicle health management
JEC	Joint Economic Committee
JPDO	Joint Planning and Development Office
kg	kilogram
L	low

m	meter
M	medium
MANPADS	man-portable air-defense systems
MJ	mega-Joule
N ₂ O	nitrous oxide
NACA	National Advisory Committee for Aeronautics
NAS	national air space
NASA	National Aeronautics and Space Administration
NextGen	Next-Generation Air Transportation System
NEXTOR	National Center of Excellence for Aviation Operations Research
NGATS	Next-Generation Air Transportation System
NIA	National Institute of Aerospace
NIC	National Intelligence Council
NO _x	nitrogen oxide
NPV	net present value
NRC	National Research Council
NSRD	RAND National Security Research Division
NSTC	National Science and Technology Council
NTS	National Transportation Statistics
O ₃	ozone
OMB	Office of Management and Budget
OSD	Office of the Secretary of Defense
OST	Office of the Secretary of Transportation
OSTP	Office of Science and Technology Policy
PA	public address
PAT	Portfolio Assessment Tool
PAV	personal air vehicle

QFD	Quality Function Deployment
RAND TST	RAND Transportation, Space, and Technology
R&D	research and development
RDT&E	research, development, testing, and evaluation
ROI	return on investment
RPV	remotely piloted vehicle
SCC	social cost of carbon
SME	subject-matter expert
SSTOVL	super-short takeoff and vertical landing
S&T	science and technology
STEM	science, technology, engineering, and mathematics
STOVL	short takeoff and vertical landing
TRL	technology readiness level
TSA	Transportation Security Administration
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
U.S.	United States
V&V	verification and validation
VOT	value of travel time
VSL	value of statistical life
V/STOL	vertical and/or short takeoff and landing
VTOL	vertical takeoff and landing

Introduction

Since the breakthrough of controlled, sustained, heavier-than-air flight more than 100 years ago, aeronautics has made remarkable strides in developing pervasive transportation capabilities, providing revolutionary national security resources, enabling space access, and making possible the controlled descent of spacecraft to earth and other planets. Much of this progress has been made by repeated and concerted efforts to address grand challenges and other research issues in the field, ranging from aircraft design to the design of efficient air traffic control systems.

Recently, however, the maturing of airplane and jet engine technologies has led to questions regarding what grand challenges and applied research themes with practical solution concepts remain in aeronautics.¹ New production jet airplanes (such as the Boeing 787 and C-17) are, in principle, much like the early Boeing 707—a “tube and wing” design (Kroo, 2004). Jet aircraft are produced globally by a relatively mature and consolidated commercial and defense aerospace industry that relies on existing design and test know-how and capabilities during research, development, test, and evaluation (RDT&E) of new aircraft, and also for the sustainment of existing aircraft to keep them flying safely and extend their life.

What, then, might drive current and future research in this apparently mature industry? How important might these drivers be financially? Are there viable applied research concepts worth pursuing? Does the U.S. government continue to have a role in advancing the civil aviation industry? Given the importance of aerospace applications to the economy and to national security—and given foreign government investments in aeronautics research—what does the United States need to do to remain competitive in the field?

A high-level perspective is needed to answer these questions. This perspective should include a decision process and framework that can help policymakers decide whether and at what levels to fund proposed applied research. These decisions should

¹ See, for example, Dr. Sliderule (1999), Walker et al. (2002), McMasters and Cummings (2001a, 2004), and Kroo (2004).

consider such drivers as social and economic goals,² governmental roles, measures of the benefits to society, and the opportunity to revolutionize or provide significantly new capabilities. Too often, similar previous efforts considered these issues from a predominantly technical perspective, specifying objectives driven by technical opportunity and ideas with only a vague tie to the higher-level goals they support, thus, they lacked a way to effectively justify the applied research and the way competing goals were prioritized in a manner transparent to nontechnical decisionmakers and the public.

Recognizing this, the National Aeronautics and Space Administration's (NASA's) Aeronautics Research Mission Directorate (ARMD) asked the RAND Corporation to develop a decision framework and provide supporting analysis on applied research theme areas to help ARMD establish and prioritize its aeronautics research plans and investments using strategic goals and objectives.

Study Approach

In response to ARMD's requests, we examined ARMD's current research programs, existing materials on their content, existing strategic explanations of these programs, available budgetary information, technical details of the programs, and broader policy and planning documents. We also examined the logical relationships and purposes of the components to try to develop an independent description of what ARMD was doing and why. We found it difficult in many cases to understand the programmatic organization relative to overarching goals and drivers.

This analysis led us to focus on developing approaches for answering the following three questions:

1. What aeronautics research should be supported by the U.S. government?
2. What compelling and desirable benefits drive that research?
3. How should the government—especially NASA—make these decisions?

As a result, we focused our effort on ways to identify government roles in research, ways to tie research efforts logically to social and economic drivers, decision metrics of relevance, and decision processes that are useful for examining and weighing alternative research options against these metrics. We combined existing data in the literature with our own expertise and knowledge to begin to examine drivers and thus illustrate

² Here "social goals" are goals that society as a whole (or major portions of society) values yet may not be explicitly or sufficiently addressed by business or current economic drivers. Examples include safety, environmental concerns, health, and privacy. We raise the topic of social goals to ask explicitly what drives research in that area and what is the magnitude or importance of those goals to help measure their importance and value. So, for example, the value of a human life is considered by some to be priceless, but government and society as a whole have limits on the extent they may go to save a life.

how the government can more explicitly qualify and quantify such drivers. We also developed and exercised decision frameworks to refine their design and develop examples of their use.

Although this work was sponsored by and largely focused on NASA, these approaches should be useful to other governmental entities involved in funding aeronautics research as well as other entities that struggle with goal-driven research in other disciplines.

In particular, we sought existing data on the fundamental societal drivers for aeronautics to provide a stronger motivational link between research and drivers both to inform decisionmaking and to justify the importance (or lack thereof) of applied research options. This monograph summarizes our findings in this effort.

Overview of a Decision Process for Aeronautics Research

Previous efforts to prioritize aeronautics research funding in ARMD were generally driven by technical opportunities loosely tied to higher-level strategic goals. That is, they started with technological challenges and were sometimes inconsistent in linking those challenges to practical applications. Moreover, the higher-level strategic goals were often not well motivated. This resulted in a “techno-centric” approach that frequently did not consider solutions in other areas that needed to be developed for a practical application to be successful. The criteria for prioritizing research and other projects flowing from these challenges were not always explicit, making it difficult for policymakers less familiar with aeronautics issues to set funding levels between challenge areas or to identify what made one topic more promising than another and for aeronautics research supporters to offer detailed justifications for their priorities or to defend them in budgetary discussions.

In an effort to improve the practical understanding of the options for advancing aeronautics through research, therefore, we develop a process for prioritizing aeronautics research that

- identifies potential grand challenges and research themes to facilitate prioritization at a manageable strategic level
- collects and analyzes data on social and other drivers for the fruits of such research to understand the relative importance of research options
- explores the technical viability of these themes to understand technical risks (i.e., likelihood of successful research)
- displays the extent of the problem being addressed and at what level of research risk to understand budgetary sufficiency and extent of research
- measures research option values using data on drivers and other strategic criteria to inform decisionmaking and oversight

- decomposes underlying technical research options to inform higher-level decisionmaking and oversight of research management actions while tying underlying technical projects to supporting strategic challenges and themes.

At the core of this process is the explicit connection of drivers to research options. Here, drivers may include a number of different factors, including current or anticipated demand, needs, wants, and desires. These, in turn, can be affected by supply, price, fashion, and other factors. We leave it to the decisionmaker to weigh the relative importance of these drivers, but we do suggest that the drivers need to be explicit and that available information (quantitative and qualitative) be collected and referenced to help quantify the size and nature of the drivers. Otherwise, linkages of the research to applications and their value become weak, vague, and not compelling, precluding an explicit tradeoff of the relative importance of these drivers.

This process of explicit consideration of social and economic drivers is the most useful when we are discussing applied rather than basic or exploratory research that has no clear connections (yet) to practical problems. Therefore, by “research” we generally mean “applied research” throughout this monograph.³ The strength of the connection between research and its application will moderate the strength of the connection that we can establish between drivers and research via metrics. The objective is to make that linkage as explicit as possible given what experts in the field know. When something is known, we should convey that knowledge—even if the connection is qualitative or only roughly known. Without that connection, it is hard for outside evaluators of research to understand and judge the value of the research, possibly relegating it to research for research’s sake in their minds. Even something as basic as studying flow physics, however, can and should be tied to practical applications whenever possible (e.g., understanding flow physics’ effects on new vehicle shapes has implications for drag and thus fuel efficiency and other performance parameters).

Of course, the core concept of applying metrics to selecting research options is useful for basic research too. Our monograph, however, emphasizes including metrics that reflect application drivers and thus is further afield if applied to basic research.

In the monograph, we exercised each of these process components to illustrate how the process can work and to establish a working point that NASA and the nation can use to begin applying it. Actual decisionmaking, however, will require the active involvement of decisionmakers and researchers in the process.

We illustrate an aeronautics research agenda driven by strategic concerns, but we stress that the ultimate goal of our work is not to identify a specific aeronautics research agenda for NASA in the coming years; rather, it is to provide an improved way for

³ ARMD’s focus on fundamental and systems research generally pursues an application focus to the research and thus is broadly applicable to this process.

NASA to identify and assess the issues it should address in seeking to help advance U.S. leadership in aeronautics.

Structure of the Monograph

Our monograph describes this decision process for answering the three questions posed above for aeronautics research decisionmaking and gives background perspectives on the economic principles involved in such decisions.

Chapter Two provides theory and methods for answering Question 1: Why and when should the government invest in aeronautics research? We discuss some theoretical economic principles to help guide decisionmaking, including a discussion of market externalities (i.e., social goods or concerns that might not be sufficiently monetized in the marketplace) and the value of estimating costs and benefits (even if only roughly) to inform research investments. We describe how to use approaches such as net present value (NPV) and benefit-cost ratio (BCR) in such rough approximations to convey what information we do know about proposed research activities and their uncertainties and to adjust for cost differences in time using discounting. We then outline a simple decision model for determining when investments should be public or private (or halted). We conclude with a short review of some of the broad trends currently affecting the aeronautics industry.

Chapter Three presents different approaches for setting research directions: benefits driven, vision driven, directive driven, and science and technology (S&T) driven. Although our focus on answering Question 2 is on benefits, it is important to also not lose the value of the other approaches that are used. Thus, we outline and describe all these approaches and their strengths and weaknesses.

Chapter Four then addresses Question 3 by bringing these different approaches together into a multidimensional decision framework to help prioritize aeronautics research. Here, we describe our insights into potential grand challenges and research themes based on our survey and analysis of drivers, policies, plans, and technical opportunities. We then illustrate a multistep decision framework for integrating this information and deciding on research options. We also iterate decision metrics that are candidates for inclusion in this decision process.

Chapter Five summarizes our observations, conclusions, and recommendations, and includes brief summaries of the main insights gained from our analysis of social and economic drivers.

Appendix A provides additional information, details, and commentary from our analysis of existing information in the literature on social and economic drivers for aeronautics.

Appendix B provides additional information, details, and commentary from our analysis of the basic technical approach options to addressing these drivers. This includes

some logical decompositions of driving challenges into fundamental approaches that can be taken as a way to convey the range of approach options for addressing aeronautics drivers.

Why and When Should the U.S. Government Invest in Aeronautics Research?

To understand the appropriate role for NASA and the U.S. government in aeronautics research, we first need to explore the government's general role in supporting research and then the societal drivers that aeronautics research can address. In this chapter, we consider the general role of the public sector in supporting research and development activities, the specific reasons the market may not adequately provide all necessary research and development activity within an industry, and issues shaping the need for public investment in aeronautics research. This includes a review of some of the broad issues likely to shape the aeronautics industry in future years and the general guidance that U.S. policy has offered for public investment to deal with them.

Role of the Public Sector in Aeronautics Research—U.S. Policy

First we ask what policies have been put in place to reflect policymakers' decisions on the question of the role of government in funding aeronautics research. Such policies reflect the legislative and executive branches of government's philosophical and political views on the role of government in society, especially when economic and technical considerations do not dictate by themselves what the role should be.

U.S. aeronautics (and thus the research supporting it) serves various purposes. Perhaps the most prevalent of these is the movement of persons, goods, and (in time of conflict) weapons. The movement of persons can occur for business or leisure. The movement of goods can occur for many reasons; aviation is particularly suitable for the rapid movement of high-value, lightweight goods. The military uses of aviation are myriad and include both delivery of weapons and observation. Aviation can also provide sensors for commercial and environmental use. Still other uses for aeronautics range from recreation for those who enjoy flying their own craft to space access and reentry.

Not all these uses are relevant for public intervention. U.S. aeronautics policy provides some guidance on what the federal government deems to be appropriate aeronautics research and development (R&D). The policy (National Science and Technology

Council [NSTC], 2006) states that, to maintain its technological leadership across the aeronautics enterprise, the United States should be guided by the following principles:

- *mobility* through the air
- *national security* and homeland defense
- aviation *safety*
- aviation *security*
- world-class aeronautics *workforce*
- *energy* availability and efficiency
- protection of the *environment* while sustaining growth.

The government's role is to support long-term innovative research (i.e., ground-breaking ideas, concepts, approaches, technologies, and capabilities that provide the foundation for future technology development) to advance a robust foundation for U.S. technological leadership in aeronautics. For national defense and homeland security, government activities should extend from basic research to advanced technology development and beyond. In sum, the policy seeks to advance U.S. global competitiveness and ensure unsurpassed military capability.

The policy also suggests that the government undertake only those roles that are not more appropriately performed by the private sector. Advanced civil aeronautics research should have well-defined goals with objective measures of efficacy that do not subsidize commercial ventures. Such research should reflect public interest in safety and security, energy efficiency, or the environment; support government infrastructure, services, or establishment and enforcement of regulations; or address gaps between drivers and current capabilities that are too risky or too far in the future for a single commercial entity to pursue.

Finally, the policy also specifies the roles and responsibilities of the executive departments and agencies in particular areas of aeronautics. For example, the Department of Defense (DoD) focuses on military aeronautics research. The Federal Aviation Administration (FAA) focuses on safety, the environment, and air traffic management research. NASA has a supporting role across all foundational aeronautics research. So, for example, the Next-Generation Air Transportation System (NGATS) is the responsibility of the Joint Planning and Development Office (JPDO) with the FAA, NASA, and others in major supporting roles (NSTC, 2006).

Role of the Public Sector in Aeronautics Research—Perspectives from Economics

We now examine what economic theory has to say about how to decide when the government should invest in research.

A “gap” often develops between the private and social return on investment (ROI) for research. This gap causes the private sector to invest in research projects at a level that might be deemed less than socially efficient. Such underinvestment represents a form of market failure and justifies government-funded research, such as that performed through NASA ARMD.

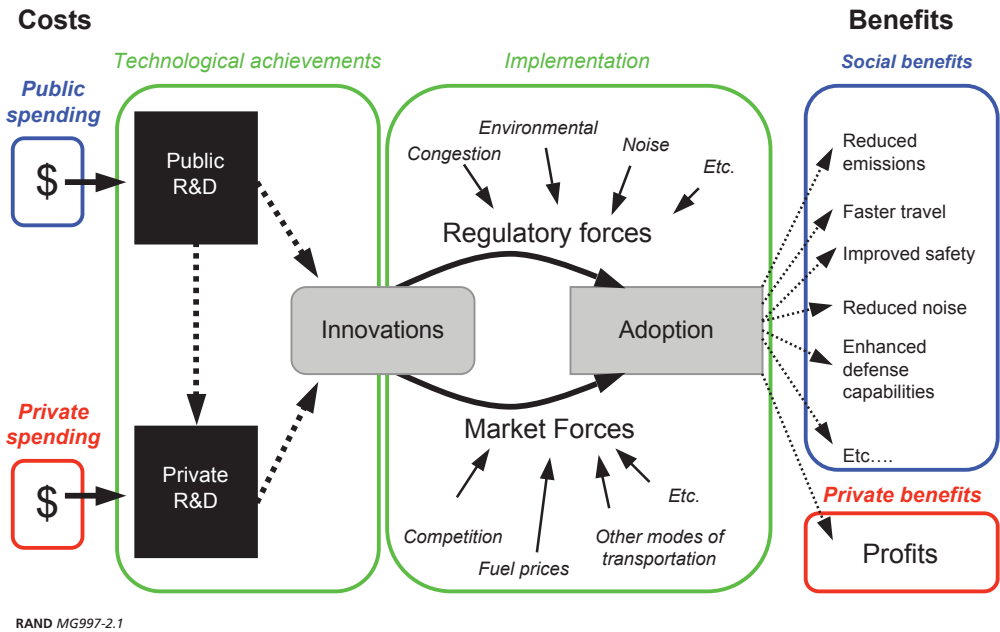
Nelson (1959) and Arrow (1959) first noted the causes of this gap. Nelson related basic science to a pure public good that is nonexcludable (i.e., no one is excluded from using it) and nonrivalrous (i.e., use of it by one does not reduce its ability to be used by others). Because such research is nonexcludable, private entities funding it may enjoy only a small fraction of the benefits generated by their investments and, therefore, not invest at a socially optimal level. Arrow (1959) identified technical risk and spillover benefits as causes for the divergence between private and social rates of return. Technical risks include those that arise from the difficulty of making a new technology interoperate with other technologies within a system. Spillover benefits include those similar to public goods accruing to parties that did not fund or conduct the research.

Measuring the ROI for research is a difficult problem. In some cases, research is so basic that it is difficult or impossible to say where the results may lead and what the benefits are. Such research does not lend itself to this kind of analysis and remains the realm of exploratory basic science organizations such as the U.S. National Science Foundation. NASA ARMD ties its aeronautics research to practical uses, and understanding the extent of the problems in those uses can help to provide a magnitude of the benefits and ROIs involved. Basic laminar flow physics, for example, could yield improvements in drag and thus fuel costs, and a discussion of the magnitude of the savings from first principles (e.g., perfect laminar flow or even zero drag) helps to set some boundaries for the possible benefits.

Also, the paths from public or private spending to social benefits are long and convoluted, as illustrated in Figure 2.1. Both public and private efforts can produce innovations. Public research and development efforts often interact with private research efforts, at times complementing them and in other instances acting as a substitute for them. Innovations can arise from several phases of research and often need to be combined with other breakthroughs before being adopted by industry. Market and regulatory forces shape innovations and help determine whether they will ultimately be adopted. Market forces shaping aeronautics innovations include competition between manufacturers, air travel demands, fuel prices, and the capabilities of alternative modes of transportation. Regulatory forces include U.S. and international mandates regarding air traffic control and congestion as well as environmental and noise emissions standards.

Successful R&D can produce a variety of social benefits, which vary by the extent of its deployment. Among other social benefits, aeronautics research may yield faster or more comfortable travel, improved safety, reduced noise, reduced emissions, and enhanced defense capabilities. Many of these advancements can also increase the

Figure 2.1
Relationships Between Public/Private Spending and the Public/Private Benefits of Aeronautics R&D



ability of industry to operate and meet consumer demand, in turn increasing the ability of the industry to generate profits.

The actual path from R&D spending to the creation of benefits can be long and highly uncertain. Many aeronautics research projects can be very complicated and require the interfacing of many technologies (some of which may not yet exist), creating significant technical risks. Even if technical challenges can be overcome, market and regulatory conditions can be difficult to predict and therefore generate uncertain payoffs. This uncertainty is amplified for research projects that have long time horizons. Many private-sector firms are unwilling to invest in very risky research projects, even if their potential ROI is great. Firms will tend to avoid R&D projects that produce benefits that they cannot realize exclusively or that do not provide a competitive advantage for a sufficient period to justify the R&D outlay. Such projects can include technologies that address environmental concerns, enhance safety, or reduce travel delay.

Government involvement in R&D can help fill the resulting gap between private incentives and public benefits by engaging in R&D in public facilities, procuring targeted R&D services from the private sector, or providing incentives to the private sector to engage in more self-directed R&D.

Prioritizing Public Research

Public research prioritization plans typically focus on technical opportunities and broad social benefits. Early research investments generally do not include formal assessments of the broader motivations behind the investments. Tassey (2003) notes that there is no standard method for assessing the effects of government research programs. In aeronautics and other areas, this has led to a gap between strategic planning and justification for research investments. Broad social drivers are often expressed at a very high level, but plans often jump quickly to lower-level technological concepts without discussing the magnitude of the social issues or the alternatives for addressing those social issues.

There are various ways to improve this process, including explicit analysis of the issues driving research and the use of objective frameworks for selecting among competing research efforts. In particular, evaluation of public research priorities can be improved by developing and assessing information on

- **Research goals and objectives:** What are the goals of the research, and what is their relative importance? What sorts of innovations are likely to result from the R&D effort?
- **Government spending requirements and time horizons:** What funding is required to achieve the research goal or objective? How long will it take?
- **Private-sector involvement:** What is the role of the private sector? What incentives do private parties have to further develop and implement research begun by the government?
- **Technical challenges:** What technical challenges exist? How likely are they to be overcome?
- **Market conditions and the adoption process:** What market conditions are required to induce adoption of technologies or processes generated by the research? How likely are these market conditions to occur?
- **Regulatory environment:** What current and proposed regulations will help or hinder adoption?
- **Public and private benefits:** What public and private benefits might be generated and in what time? How uncertain are the benefits? What are the sources of uncertainty, and what are their effects?¹

When considering research priorities, it is important to develop and estimate answers to all of these questions, not just the most immediate ones. This would allow us to better understand the long-term risks and rewards of pursuing a grand challenge or research theme. Are there overwhelming development, market, infrastructure, or regulatory challenges that would make it very difficult or costly to reap the rewards of

¹ See the discussion of uncertainty in Office of Management and Budget (OMB) (1992).

successful research in question? In an automotive example, we might be able to technically produce an efficient hydrogen-powered vehicle, but the hydrogen fuel delivery infrastructure is a major hurdle to be considered and addressed, despite the technical attractiveness of the vehicle itself.

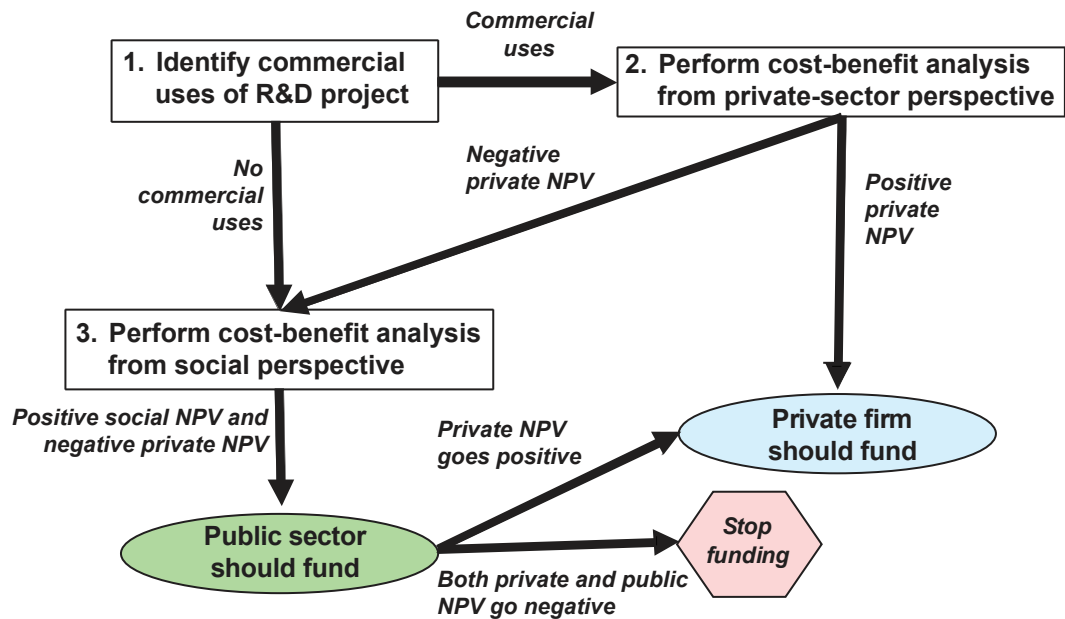
It may be difficult to quantify or even answer these questions in an in-depth manner, but attempts to address them to our best level of estimation can help identify obstacles to the assumed benefits, help prioritize among alternatives, and avoid naïve research investments.

Using NPV and BCR as Tools to Inform Public and Private Research Investments

When benefits and costs can be estimated, the Langford-GRA model (Vonortas and Hertzfeld, 1998) can help prioritize public research efforts (see Figure 2.2). Even if precise estimates of project benefits and costs are not possible to make, the Langford-GRA model can help one reason through whether a research project should be public or private (or not funded at all).

The first step in the Langford-GRA decision model involves identifying the (eventual) commercial uses for a prospective R&D project. If there are commercial uses, then the second step is to perform a private-sector cost-benefit analysis specifically

Figure 2.2
Langford-GRA Model of Public Sector R&D Prioritization



SOURCE: Vonortas and Hertzfeld (1998).

to determine whether the project is expected to have a positive NPV to the investor.² Those that have a positive NPV should be funded by the private sector and need not be further considered by public policymakers.³

Research projects with a negative NPV, as well as those identified in the first step without any commercial uses, proceed to a third step in the prioritization—a cost-benefit analysis from a social perspective. A project with a positive social NPV (and, as previously determined, negative private NPV) becomes one that the public sector should consider funding until periodic monitoring determines that private NPV has become positive, at which point it would be more appropriate for a private firm to fund it. Alternatively, if such monitoring finds that public NPV has also become negative, then the project's funding should be halted.

Note that this model provides a conceptual way of thinking about the transition of research between the public and private sector, as well as a determination of when to stop funding both public and private projects.

Although NPV can be difficult to calculate precisely, especially for early research projects, this approach helps highlight the core issues to consider in determining whether public or private investment is most appropriate for a project. Even a rough order-of-magnitude estimate⁴ would help to convey a sense of the magnitude of the relative investments, risks, and rewards in question. Such estimations would help government agencies, departments, and Congress understand the considerations, better explain the prudent use of taxpayer dollars, and make decisions based not only on priorities but also on some sense of the benefits to society.

The key determinant for the government is a positive NPV for society—not for a single private firm. This is reflected in the current U.S. aeronautics policy (NSTC, 2006, p. 9), which states that

The Federal Government should only undertake roles in supporting aeronautics R&D that are not more appropriately performed by the private sector. . . . The appropriateness of Federal investment in such research must be justified by an assessment indicating that the benefits of such R&D would occur far in the future or the risks would be too great for non-Federal participants, and the results from the research would not be appropriable to a single entity. In these cases, Federal

² Here, we use the concept of NPV to accommodate the inflationary factors of investments and benefits over time, reflecting the fact that benefits from near-term investments in research may be in the (sometimes distant) future. Although NPV may seem impossible to calculate, we suggest that some kind of rough estimates do provide perspective on the costs and benefits involved. Otherwise, decisionmakers have to rely on very subjective desires, preferences, and likes, independent of a sense of the costs and benefits from research.

³ See the discussion of important caveats to this approach below as well as the guidelines and discussion of benefit-cost analysis of federal programs in OMB (1992).

⁴ An “order-of-magnitude” estimate is approximated to a factor of some number, usually 10. Examples include indicating whether we are talking about millions of dollars, tens of millions, hundreds of millions, etc. Thus, such a rough estimate gives a sense of the general magnitude without regard to precision within it.

R&D investment must be the best means to achieve the objectives as opposed to other means such as regulatory, policy or tax incentives.

The largest deviations between social NPVs and private NPVs are likely in research areas where the private sector is unable to fully capitalize on a social benefit it might generate. In aeronautics, this is more likely to be the case with research targeted in such areas as these:

- *The environment.* Aircraft emit carbon dioxide (CO₂) and other gases that can contribute to global warming or other environmental problems. Airlines operating these aircraft do not (currently) pay the costs that can result from these emissions, and therefore they have little reason to invest in new technology. Public intervention can help reduce these costs by investing in technologies that would reduce aircraft emission of these gases.⁵
- *Congestion mitigation.* Growing demand on the air transportation system has led to generally longer and more frequent delays. Airlines will wish to reduce delays for their own customers but have few incentives to worry about any congestion costs their operations impose on other carriers. Public investments can help address this problem by improving air traffic management or by launching other efforts to improve transportation capacity in crowded markets.
- *Improved safety.* Incidents resulting in injury, death, or merely negative publicity for air travel adversely affect the aeronautics market. Continuing public research can help improve safety and show the general public that air travel safety is a priority.
- *Noise near airports.* Aircraft operations result in noise affecting those who live near airports. Put another way, those living near airports “pay” through increased noise from the airport even if not necessarily benefiting from it. Public investment can reduce (and, in many places, has reduced) this cost through initiatives to produce quieter aircraft, to provide noise abatement in residences, or to relocate persons who live near airports. Noise reduction can also foster acceptance of aviation and its contribution to economic growth—a benefit not likely to be exclusively realized, and therefore not provided, by a single private party.

Important Caveats for the Use of NPV, BCR, and Related Measures for Early Research Decisionmaking

It is important to recognize the strengths and limitations of the use of NPV and other highly quantitative measures in making early research decisions. Our objective here is to use a tool that allows the analyst and decisionmaker to explicitly recognize costs

⁵ Alternatively, the government could impose a carbon “tax” or other regulatory mandate on airlines to monetize the responsibility and drive the public sector to make efficient investments and decisions to mitigate carbon emissions. This would shift the benefit from the public sector to the private sector in this decision process.

and benefits, public and private roles, and the concept of discounting future benefits against current costs using a discount rate. Our point is that although we often do not know these factors accurately and precisely, we do know something about them, and that something can be useful to the decisionmaker as long as he or she is aware of the inherent limitations of our estimates and the potential biases of the estimators.

Difficulties and uncertainties include the lack of consideration of unforeseen benefits as well as the likelihood of underestimated costs from unforeseen R&D difficulties. Research experts may have a natural bias to overestimate benefits and underestimate costs. Still, an explanation of expected benefits will help the decisionmaker understand the source of the benefits and give a sense of whether the quantified benefits estimate is seriously overstated. Likewise, an explanation of the source of the costs (e.g., from research hurdles and infrastructure issues) conveys more information about these challenges and helps the decisionmaker develop a sense of whether the quantified costs are seriously understated.

Second, there may be value for a fundamental research organization such as NASA to consider funding early research steps that currently appear to have a negative NPV so as to inform an updated NPV in the near future, especially if the potential benefits might be large. That way, NASA can explore and seed options in a low-cost way to improve the fidelity of NPV estimates in future funding decisions.

Third, the simple fact that an NPV estimate is positive may not be sufficient by itself to trigger an investment decision. Measures such as the BCR discussed below allow a relative comparison between benefits and costs, allowing comparisons of relative returns. Government decisionmakers may also want to set a so-called hurdle rate for the NPV and BCR at a significant positive size to account for and hedge against the uncertainties in the estimates. Thus, only investments of a large NPV greater than the hurdle rate would be chosen for investment. Finally, the choice of a discount rate in the calculation (see the discussion below) will have a very significant influence on the resulting NPV. Besides worrying about people manipulating the decisionmaking system by selecting discount rates that favor their proposed line of research, the issue can be viewed in philosophical terms: How does the government want to balance current costs against future gains? Put differently, does an agency such as NASA want to focus on near-term or long-term gains (or perhaps both, using two different discount rates in separate calculations)?

These issues are important in that they point out the limitations of the approach and they should be remembered when interpreting the results. Moreover, this discussion reemphasizes that the actual decision criteria for a certain situation should be selected on the basis of the decisionmaker's needs, the types of research options under consideration, and the need to examine the options from multiple perspectives. Often, some information is available on all these points (benefits, costs, research challenges, uncertainties, implementation challenges, etc.), and they should be conveyed to the decisionmaker and made as explicit as possible.

Practical Aspects of Estimating NPV, BCR, and Related Measures

The discussion above sets a philosophical context for linking research to benefits (as defined by specific drivers) and costs. NPV is but one conceptual measure that can be used to help understand this linkage. Others may be just as or more appropriate, depending on the data available. Examples include such other economic measures as BCR and internal rate of return (IRR) (see Tassey, 2003)—all variations on the same conceptual approach. BCR is similar to NPV in that it compares the present value of costs and benefits but in a ratio rather than a difference. IRR is the “. . . discount rate that makes the NPV of a project zero (the equivalent of benefit-cost ratio of one)” and is useful when comparing it with other yields or rates, such as the opportunity cost of capital (Tassey, 2003). Table 2.1 shows an example of the results of such a systematic analysis to estimate NPV, BCR, and other performance metrics.

Although useful, such an in-depth analysis may not be affordable or even practical given readily available data. In such cases, we seek to extract from the domain experts some sense of the approximate (orders-of-magnitude of) costs and benefits involved.

Of course, for various reasons we have to be cautious about the information provided by domain experts. Researchers tend to understand developmental and implementation challenges less and therefore may underestimate the costs associated with those challenges. Experts commenting on their own lines of research or areas have a natural bias to try to make their approaches look better than others. Research is also inherently filled with uncertainty, so an expert can estimate only the “knowns”—not the “unknown unknowns.”

Consider the notional example in Table 2.2 for an unspecified concept. Here we show the costs, benefits, and number of years for three cases: low, medium, and high. Note that a single case can be used if desired, but this approach allows the experts to convey a sense of the range of uncertainty in their estimates. NPV and BCR are calculated using an illustrative public discount rate of 5 percent and a private discount rate

Table 2.1
Example Economic Impact Assessment of a Portfolio of Projects

Metric	Estimate
Total investment costs	\$119 million
Net present value	\$840 million
Benefit-cost ratio	10.5
Social rate of return	80%
Total producer surplus	\$538 million
Total consumer surplus	\$1,129 million

SOURCE: Tassey (2003), based on Gallaher and Kropp (2002).

Table 2.2
Notional Example of Rough Estimates of NPV and BCR (\$ millions)

Stage	Time (years)			Public Costs			Private Costs			Public Benefits			Private Benefits		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Inputs															
Current research	3	3	3	5	5	5	0	0	0						
Subsequent research	3	4	5	10	20	100	10	20	50						
Development	2	3	4	0	0	50	50	100	200						
Production and implementation	5	5	5	0	0	0	50	100	250						
Sustainment	10	10	10	0	0	0	5	10	20	80	100	200	500	650	800
Outputs															
NPV				290	297	-103	725	620	208						
BCR				8.8	5.0	0.8	5.4	2.8	1.3						

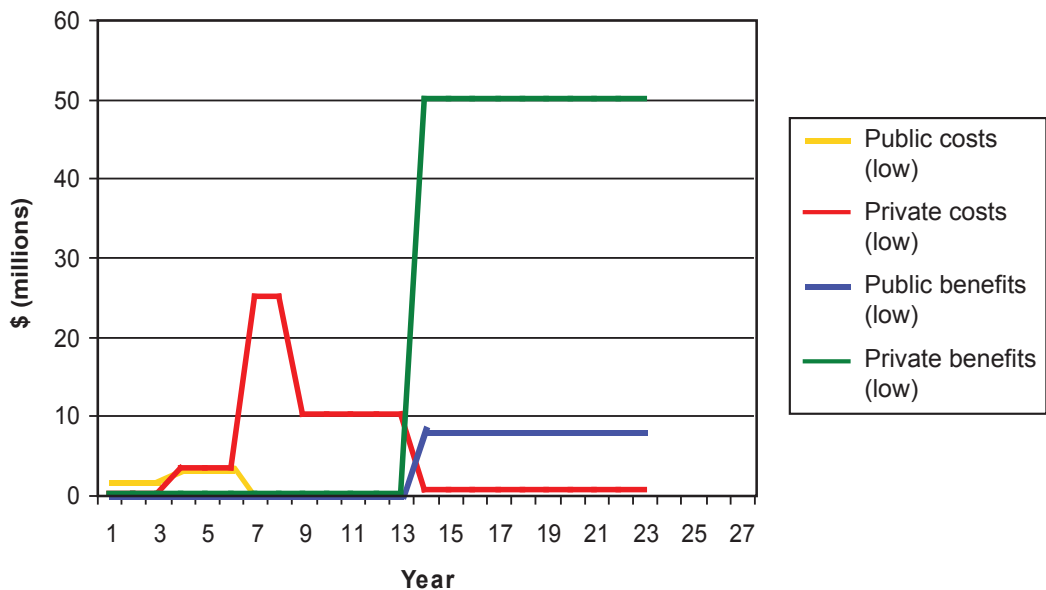
NOTES: This table is purely notional with no specific topic. Uncertainties are expressed using low (L), medium (M), and high (H) ranges. Costs and benefits are totals accrued over the time period indicated.

of 10 percent.⁶ A hurdle value of \$100 million was set for NPV and 1.5 for the BCR. Actual discount rates for cost analysis of government programs should use the current OMB guidelines and annually updated rates for the fiscal year (see OMB, 1992, 2009). The costs and number of years for each case are estimated roughly across the stages of the concept: current research (being solicited for funding), subsequent research, development, production and implementation, and sustainment (or time of fielding) of the concept. In this example, the benefits are not realized until fielding and are thus listed on the “sustainment” line. Figure 2.3 shows the low values from Table 2.2 across time to show how the costs are incurred in the early years and the benefits in the later years. Stages are sequential without overlap, and the length of each stage can be different for the low, medium, and high cases (e.g., research might take longer in the high case).

We then take these inputs and calculate low, medium, and high NPVs and BCRs using the low, medium, and high costs and benefits (respectively). Cross-pairing could also be done (e.g., low benefit with high cost), but that is not shown in this example. A hurdle value was set for NPV and BCR to indicate whether the value was marginal. Thus, if the value is below the hurdle value but above positive and 1.0 (respectively) for NPV and BCR, then the cell was shaded yellow. For example, the BCR for high private was below the hurdle value of 1.5, so that cell was shaded yellow.

⁶ A private discount rate will be tied to a company’s opportunity cost of capital. These opportunity costs approximate the borrowing rate a company must pay on new debt, which is tied to commercial lending rates that are above the rates paid on treasury notes and thus above public discount rates.

Figure 2.3
Costs and Benefits Time Line from the Low Figures in Table 2.2



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Thus, in this notional example, a simple spreadsheet calculation allows someone to convey a sense of the costs and times involved as the concept moves from research to fielding. The estimates of benefits can be extracted from analysis such as that presented in this monograph (e.g., in Appendix A).

Public and private decisionmakers would use the NPV and BCR from Table 2.2 as one metric for the decision whether to fund this research option, as shown in the flowchart in Figure 2.2.

The essence of this approach is to convey some sense of the extent of the currently requested research; the remaining subsequent research, development, production and implementation; and sustainment costs. For research with an application focus, some sense of the magnitude of the challenges in these levels should be obtainable by knowledgeable researchers who have good connections with practical implementation experts in industry.

Other types of qualitative measures can be used at this stage. Examples include cost versus expected value or utility.⁷

⁷ See, for example, Silbergliitt and Sherry (2002), Silbergliitt et al. (2004), Adumitroaie et al. (2006), Landree et al. (2009), and Chow, Silbergliitt, and Hiromoto (2009).

Role of the Public Sector in Aeronautics Research—Technical and Systems Maturity Perspectives

In addition to policy and economic theory perspectives, it is also useful to examine technical considerations related to technical and systems maturity when considering the appropriateness of public investment in the aviation industry. It is useful to stratify products by their stage in the RDT&E continuum. This continuum starts with basic research that matures through the development of actual aeronautics products. As a product matures from research toward use and sustainment, its benefits are more likely to be associated with specific stakeholders and communities, who may be more appropriate supporters. Individual steps in this continuum originating in fundamental theory and science and concluding with product support can include

- theory and science
- technical aspects (i.e., the know-how of applying theory and science to practical problems)
- components (i.e., parts of a larger system)
- system integration
- demonstration (i.e., building prototypes both to learn from the prototyping and to demonstrate the concept and its maturity)
- development (i.e., the practical creation of a product)
- production (i.e., the generation of copies of the product for sale or application)
- use and sustainment (i.e., the use of the product and the continued support to keep the product operational).

The ultimate use of a product will help determine government's role in supporting it. More precisely, if a product is likely to be used by the government (e.g., for space exploration or military uses, which provide broad social benefits), then the government may stay involved throughout these stages and the life of a product. However, if a product emanating from government research is more likely to be used for commercial purposes, then the private sector should have more of a role as product development stages advance and benefits become more immediate and direct. A similar continuum is offered by considering the technology readiness level (TRL) of a system or concept.⁸ As the technological readiness of a project advances, it becomes more suitable for private than public support.

There are reasons for government to continue support for technology that may initially seem strictly commercial, however. A good example of this is reduced aircraft fuel consumption. More efficient aircraft save operation costs to airlines (a private benefit). Nevertheless, lower fuel consumption also results in fewer carbon emissions, reduced national petroleum dependence, and often lower pollution as a result of more

⁸ See Mankins (1995) and DoD (2005).

efficient fuel burning. Thus, the government may choose to fund continued research in fuel efficiency to realize the public good of a cleaner atmosphere and other strategic objectives.

The extent of commercial applications can determine the state at which the government should stop providing research investments. Theoretically, this state could be determined by estimating the NPV, the extent of follow-on R&D needed, and remaining steps toward product maturity. Practically, this may not be easy to determine. Where and when government should invest in the latter stages of R&D is made still more difficult by the interests of the commercial sector in obtaining as much external support as possible, and of the government in turning research responsibilities over to the private sector as soon as possible. This often leaves a gap in funding for individual concepts and technologies.⁹

The discussion to this point has been very theoretical. The skeptical reader will wonder how practical all this is (i.e., can we really estimate NPVs to any degree for research). The remainder of the monograph is intended to present approximation methods for roughly estimating the potential benefits of a research area (see Appendix A for detailed examples). Estimates of the potential gains that a line of research may provide need to be made by experts in the field. So, for example, what kind of magnitude in fuel reduction might a new engine design or a new vehicle shape provide? In many of these cases and despite uncertainties, experts do have some sense (or hope) for their concepts, and it is useful to extract these estimates from them, update these perspectives as we learn more about the risks and reduce the uncertainties, and provide some basis for objective decisionmaking. Such insights have been used in the past in exercises to manage the portfolios of research investments relative to stated objectives.¹⁰

Preliminary Views on the State of Aeronautics Research

Finally, we present some brief, preliminary views on the state of aeronautics R&D to help provide some context on where the field is and, therefore, what roles of the government might advance it. We include examples of broader social and technical trends, a discussion of how these trends may affect aeronautics, and an overview of the state of aeronautics research at NASA.

Public aeronautics research will likely need to respond to what is occurring elsewhere in the world of aviation. Such considerations must include several general questions regarding supply and demand. Regarding supply, relevant questions include the

⁹ For a further discussion on the gap between public and private investment and on the Small Business and Innovation Research Program for the DoD, especially on the need for “transitional” funding, see Held et al. (2006). For more on TRLs, see Mankins (1995) and DoD (2005).

¹⁰ See, for example, Silberglitt and Sherry (2002) and Silberglitt et al. (2004).

conditions that might affect how air travel is controlled, what increases in air traffic capacity might be possible with improvements in information technology, and what advances in material science might affect aircraft performance and life. Regarding demand, relevant questions might include those related to the uses of air travel by tourists needing affordable travel, by business leaders needing fast and comfortable travel, and by producers and consumers shipping or receiving goods. Still other demand questions relate to surveillance made possible by aviation, weapons delivery and other uses by the military, and space access.

Some broad indicators of likely supply and demand issues are evident in recent developments both in other nations and in trends within the industry. The European Union (EU) is likely to continue its cost-shared research investments, albeit with tight budgets. This approach, in the estimate of the National Institute of Aerospace (2005), has succeeded in pushing some elements of the EU civil aviation manufacturing industry ahead of that in the United States, sometimes making Airbus the leader in civil aircraft sales. Asia is also likely to invest significantly in its aviation industry and rise to challenge U.S. and Europe leadership in it, although its focus is more likely to be on commercial vehicles and (initially) less sophisticated military aircraft than are produced in the West. At the same time, development abroad can provide not only increased production competition but also increased market opportunities and increased travel opportunities, increasing the demand for aviation.

Other broad international issues that may affect the aviation industry relate to energy and fuel availability. Growing international demand may result in increased competition for, or instability in, supply. Fuel economics are likely to affect the demand for new capabilities, including, for example, that for more fuel-efficient vehicles. At the same time, energy supply issues may be less important for the aviation industry than for ground transportation, given the relatively low share of fuel consumption by aviation. As a result, the primary energy issues for aeronautics in future years are likely to remain related to energy density (that is, the amount of energy available in a given volume of fuel), rather than cost, when it comes to the development of potential alternative fuels.

Within aviation, the current state of the industry points to several likely developments in coming years and some less likely, as well as to varying drivers for civil aviation research. The military is likely to continue exploring hypersonic aircraft capable of traveling at least five times the speed of sound. There may be some potential dual uses for such aircraft, resulting in supporting roles for NASA in developing them. Rotorcraft are likely to remain in niche roles, with the military again as the lead developers, but also with some possible roles for NASA to play in further advancing civil aviation niches. Environmental effects on aeronautics research are likely to wax and wane with political trends. It is too early to tell whether there will be large new opportunities for new aeronautic vehicle concepts, such as blended-wing bodies, morphing-wing aircraft, or active-flow-control aircraft. Another potential new product called personal

air vehicles is more likely to pose challenges in aircraft control, automation, safety, and the air traffic system rather than in vehicle design. Finally, U.S. dominance in the commercial aircraft marketplace has been reduced by foreign competitors that are successfully becoming peers, and the aeronautics field itself is not certain whether major breakthrough concepts would yield sufficient gains to warrant their application or whether we are on a path of evolutionary improvements in components on the same tube-and-wing concept. Current research hopes to inform this uncertainty, and its resolution may help dictate the kinds of research most appropriate to pursue.

These trends point both to some likely drivers for aeronautics research as well as to some remaining open questions. Regarding aeronautics problems and challenges, these trends may increase demand for point-to-point mobility, but within cost limitations. Such limitations and other issues (e.g., air traffic capacity) also suggest a need to consider other modalities. In some congested areas, for example, the federal government may wish to consider developing high-speed rail to connect cities within a region instead of attempting to add additional air carrier capacity.

Remaining open questions range from the role of international competition to the development of aeronautics commodities and are possibly beyond the interest of public research initiatives. Regarding international competition, policymakers may wish to consider when the United States must be the leader among all nations, when it must be a leader with others, or when it may cede interests in certain sectors (as it currently does in commercial shipbuilding and in many electronics manufacturing sectors). For example, policymakers are likely to want the United States to be the single leader among all nations in issues and initiatives regarding military aviation as well as in civil aviation industries with high profit margins and that demand high workforce skill levels (and commensurate salaries). Policymakers may be willing to have the United States share leadership with a few other nations in some other areas, such as dual-use military and civilian aviation for air cargo. By contrast, policymakers are less likely to be concerned with areas of the aviation industry that are becoming akin to commodities.¹¹ Rather, they are more likely to be concerned with whether the public is willing to invest at the levels needed to advance or maintain U.S. leadership, whether public investment is needed to ensure such leadership or only to complement private initiatives, and the reasons some projects might elicit public support.

External Trends and How They May Affect Aeronautics

Non-aeronautics societal and technical trends are also likely to affect the demand for aeronautics. Here are some illustrative examples.

¹¹ Commodities are articles of commerce that are generally interchangeable regardless of source (Merriam-Webster, 2010). In aeronautics, components of aircraft may be becoming commodities. One may also ask if aircraft are becoming commodities in that airlines consider them interchangeable to some degree. However, aircraft are complicated vehicles with some differences between manufacturers (as with automobiles), and it is beyond the scope of this monograph to examine the question of whether aircraft are or will become commodities.

Societal. The National Intelligence Council estimates that globalization will increase through 2020 (NIC, 2004). This will likely increase the use of aeronautics for global transportation. At the same time, pandemics such as swine flu (World Health Organization, 2009) might also result in short- to medium-term decreases in global transportation demand, although their severity and resulting effects remain uncertain.

Technical. Technology will also continue apace with globalization (see, for example, Silbergliet et al., 2006a, 2006b). Some of these advances may help advance aeronautics. Technology likely to boost aeronautics includes increased computational power and modeling capability for improved computational fluid dynamics (CFD) simulations; advanced materials for lighter vehicles and dynamic shape modifications (“morphing”); (semi-)autonomous controls enabling increased use of unmanned and autonomous vehicles; and advances in micro air vehicles (McMasters and Cummings, 2004; Kroo, 2004).

As we will see in Chapter Four and the appendixes, some of these trends generate not only new benefits but also additional challenges. For example, extensive use of composite materials in commercial aircraft can reduce aircraft weight, thereby increasing fuel efficiency and aircraft capacity, but it also raises questions of how to maintain safety levels typical of better-known metal structures as well as how to repair composite structures. Similarly, a shift to a new air traffic control system with large increases in capacity also poses questions of how to ensure safety while using untried control techniques and technologies to deal with an increase in aviation traffic.

NASA’s Involvement in Aeronautics Research

Finally, we briefly review the role NASA has played in aeronautics research and its current state to provide some perspective on current government activities in aeronautics. There are other significant efforts elsewhere in the government involved in aeronautics research—especially in the DoD and the FAA—but it is beyond the scope of our study to review their efforts.

NASA and its predecessor, the National Advisory Committee for Aeronautics (NACA), have a long history of fostering advances in American aviation (see, for example, Bilstein, 1989). NACA’s work on airfoils and engine cowlings, as well as its work on such problems as icing, helped to develop an early American lead in aviation. The United States surrendered some of this lead in the years following World War II when European nations made advances in gas turbines and high-speed flight. Nevertheless, NACA’s cooperative programs with the military flourished, which helped to develop the X-1 and X-15 aircraft.

Growth in U.S. federally funded aeronautics research accelerated after the 1957 launch of Sputnik and the transformation of NACA into NASA. Given larger budgets, NASA established new research programs in both astronautics and aeronautics. Its aeronautics programs in the post-Apollo era included hypersonic flight, control-

ling pollution, reducing engine noise, and improving fuel economy. Nevertheless, as Bilstein (1989) notes, the agency was not always clear in its missions and purpose.

Today, NASA aeronautics research efforts (especially its research into non-space-related flight) are mostly managed under ARMD. ARMD currently conducts “fundamental research in both traditional aeronautical disciplines and relevant emerging fields for integration into multidisciplinary system-level capabilities for broad application” (NASA, 2010a).¹² The specific interests of ARMD include helping to create the Next-Generation Air Transportation System (NextGen) to increase the capacity of the air traffic system,¹³ and engaging in applied research to reduce noise and emissions while improving aircraft efficiency, performance, and safety.

ARMD has pursued this research on diminishing resources. After general increases in the 1960s and 1970s, a moderate decline in the 1980s, and a resurgence in the 1990s, funding in the 2000s showed a sharp and nearly steady decline since the late 1990s (see Figure 2.4; also Paul, 2001; National Research Council [NRC], 1981, pp. 43–44, and 1999, p. 8). Since its peak at about \$1.8 billion (in fiscal year [FY] 2008 dollars) per year in the mid-1990s, ARMD funding is now around \$600 million to \$700 million, its lowest level (in adjusted dollars) in more than 40 years.

Note that recent accounting changes, such as removing Center Maintenance and Operations (CM&O) burdens on research directorate budgets,¹⁴ make it difficult to quickly compare aeronautics budgets across years. For example, the current aeronautics budget is not subject to CM&O burdens and is thus worth more than prior burdened budgets from FY 2008. Also, some aeronautics-related research is being performed on the space accounts at NASA. It was beyond the scope of this study to perform an in-depth historical budgetary analysis of these factors. Nevertheless, these figures convey a sense of the general decline in aeronautics research at NASA.

ARMD research is carried out by five research programs (NASA, 2010a). These, and their respective enacted FY 2010 budgets, are:

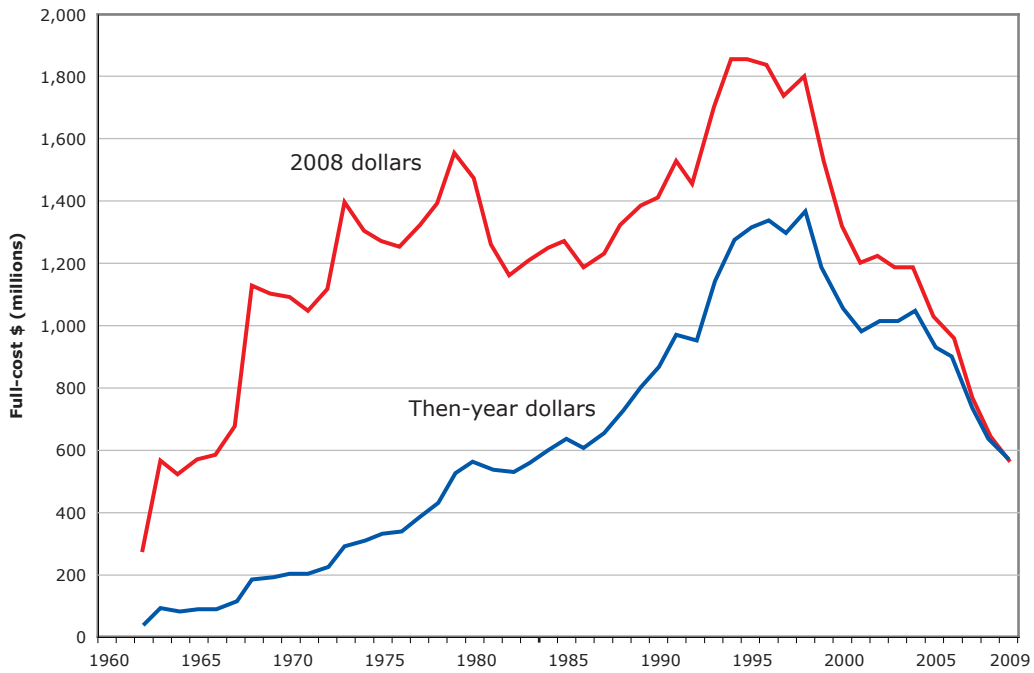
- Fundamental Aeronautics, \$220 million
- Airspace Systems, \$80 million
- Aviation Safety, \$75 million

¹² Strategizing at ARMD has recently added a new systems-level research program called the Integrated Systems Research Program. This program “focuses on maturing and integrating NextGen technologies into major vehicle/operational systems and subsystems that will address these national challenges” (NASA, 2010b). Thus, ARMD has added onto its foundational research to address integrated systems opportunities and move research results closer to systems-level demonstrations.

¹³ NASA ARMD’s work is just one contribution to the overall public-private NextGen effort coordinated by the NextGen Joint Planning and Development Office (JPDO, undated), which includes contributions by the FAA.

¹⁴ For example, CM&O became a separate budget item in the FY 2009 budget request but was charged to mission directorates in FY 2008 and earlier (see NASA, 2008, 2007).

Figure 2.4
NASA Aeronautics Budgetary Funding History (1959–2009)



SOURCE: Roy V. Harris, Jr., in "From the Chair: NASA Aeronautics—Connecting the Dots Between Funding and Leadership," *Aeronautics and Space Engineering Board News*, Vol. 1, Issue 3, pp. 2–3, Washington, D.C.: The National Academies, December 2008.

NOTE: 2008 dollars are from the Federal Reserve Bank of Minneapolis inflation calculator, revised 11/4/08.

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- Aeronautics Test Program, \$72 million
- Integrated Systems Research, \$60 million.

Funding for each of these programs and the overall program budget is projected to remain relatively steady in coming years, increasing from a total of \$507.0 million in FY 2010 to \$600.3 million in FY 2015 in unadjusted dollars. Although this will represent a level of stability in funding that ARMD has not seen in several years, the relatively low total amount underscores the need to prioritize limited resources for accomplishing the greatest good.

Different Approaches for Setting Research Directions

The top-level national goals and areas for aeronautics research are relatively consistent across published reports, plans, and proposals. Common themes include increasing aviation safety, efficiency, capacity, flexibility, comfort, and U.S. competitiveness; reducing environmental effects and travel time; and supporting space exploration and national defense.

What is not always clear is what the United States should or could do in each of these broad areas or how it should prioritize research efforts across them, making tradeoffs or focusing on some at the expense of others to ensure a critical mass of research to improve the odds of useful results at the end.

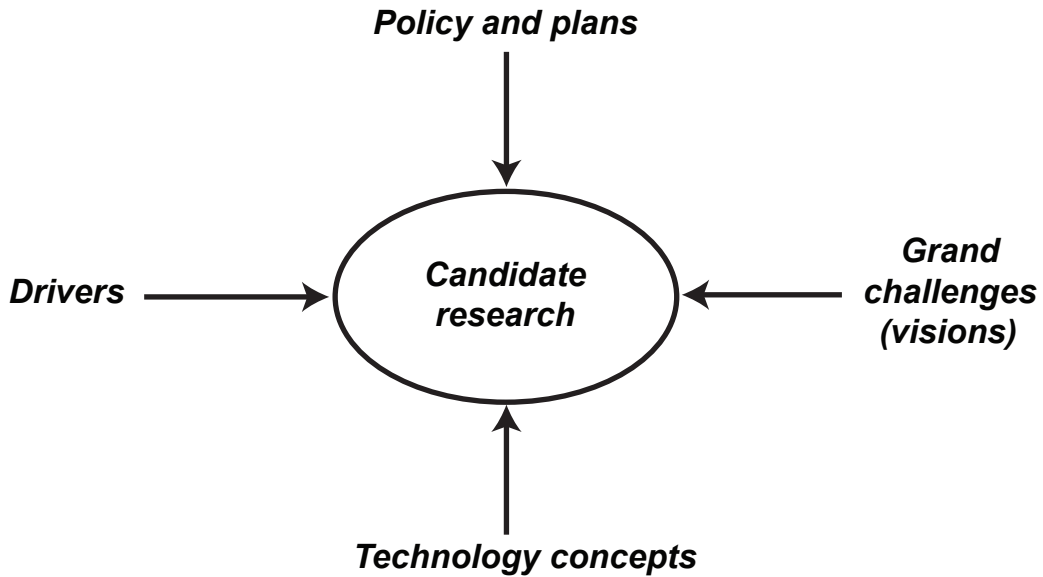
Research initiatives may affect not one but multiple goals. For example, more efficient engines would contribute to efficiency, competitiveness, environmental improvements, and national security. Conversely, some initiatives might promote one goal while conflicting with others. For example, fuel additives to reduce fuel flashpoint temperatures for increased safety might decrease efficiency, produce additional pollutants, and have an indeterminate effect on competitiveness.

In this chapter, we review key approaches that policymakers can use to identify and select research directions and priorities. We explore how research program directions can be informed by considering four different approaches: grand challenges, social and economic drivers, national policy guidance, and technical opportunities identified by subject-matter experts (SMEs), followed by some NASA-specific considerations (see the schematic in Figure in 3.1). In each case, we explain the approach, illustrate with a specific example or two, and discuss the potential benefits and drawbacks of each approach when used alone. We also discuss how a strategic planning effort that integrates these different approaches can result in a more transparent and structured process.

The following chapter then illustrates an integrative decision framework along these lines.

More extensive information and data from our initial use of these approaches as applied to aeronautics research can be found in the appendices.

Figure 3.1
Dimensions That Should Be Integrated into Aeronautics Research Decisionmaking



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Social and Economic Drivers Approach (Benefits-Driven)

Understanding the compelling drivers of research is important if one wants to construct a useful and defensible research program. Social and economic data provide a valuable and often quantitative means for understanding drivers and comparing them (especially when they can be monetized even if only roughly).

Economic factors cover an extremely broad range of considerations. In some cases, the cost of aeronautics research can be weighed against the potential direct future economic benefits. For example, anticipated fuel efficiency improvements multiplied by the cost of fuel would provide an estimate of their value to society. Likewise, technologies for reducing air traffic delays multiplied by the average value of passenger time would produce a measure of societal benefit. Additionally, other issues, such as safety and the environment, can be analyzed in an economic manner and are considered part of this approach. By using monetary estimates for the value of human life or for the effect of emissions on public health or global warming, one can produce comparisons with both the expected investment cost of the research effort and the economic benefit across the various proposed research efforts.

A few key examples of this approach are described below. More comprehensive analysis into other issues and additional economic data can be found in Appendix A, including:

- air capacity demand
- air travel delays
- aviation safety
- fuel costs and consumption
- aviation emissions
- noise emissions
- fostering competitiveness.

Illustrative Examples of Using Data to Quantify Economic and Social Drivers

We now examine some illustrative economic and social data from Appendix A that begin to shed more light on possible drivers of aeronautics research.

Example 1: Air Transportation Capacity Drivers. Consider, for example, the need for increased air transportation capacity in the United States. What do the historical data say about capacity demands historically, and what are the projections? Do dips in capacity demands from economic recessions or airplane crashes change these long-term trends?

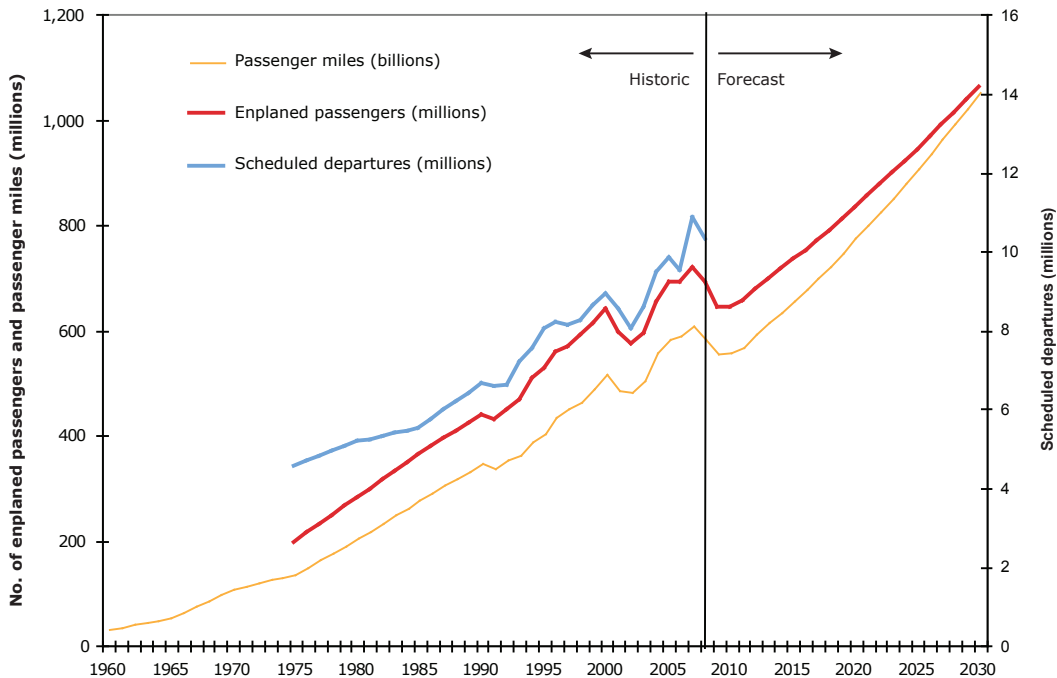
For the past several decades, with the exception of a brief period following the September 2001 terrorist attacks against the United States, the demand for air travel has steadily increased (see Figure 3.2). Since 1975, the number of passenger miles has increased more than fourfold, the number of enplaned passengers¹ has increased nearly fourfold, and the number of scheduled departures has more than doubled. Over the next 17 years, the numbers of passenger miles and enplaned passengers are projected to continue growing by about half by 2025.

Data for general aviation on a passenger mile basis are not available, but hours flown are (see Figure 3.3). Over the next 17 years, the number of general aviation hours flown is forecast to increase by a third (compared to a half for commercial aviation). The number of general aviation takeoffs and landings (called “airport operations”) has reduced by about 25 percent since 2000 but is forecast to increase almost back to the 2000 level by 2030. In comparison, the number of air carrier operations has reduced as well but is forecast to grow more—about 50 percent more by 2030.

Therefore, there is both historical and forecast support that there is a need to increase airspace capacity despite perturbations in the demand trends. These data, of course, do not monetize the value of the increased demand (which would be valuable to know but would require further analysis), but they begin to quantify the value and provide insights into the trends that are sometimes missing in arguments for increased airspace capacity investments.

¹ Enplaned passengers are persons receiving air transportation from an air carrier (see, for example, BTS, 2007, Table 1-34).

Figure 3.2
Trends in Aviation Industry Usage



SOURCES: Historic data from the Bureau of Transportation Statistics (BTS) (2010b), Tables 1-34 and 1-37; forecast data were calculated based on FAA (2008), Table 5.

NOTE: BTS data are available only through 2008.

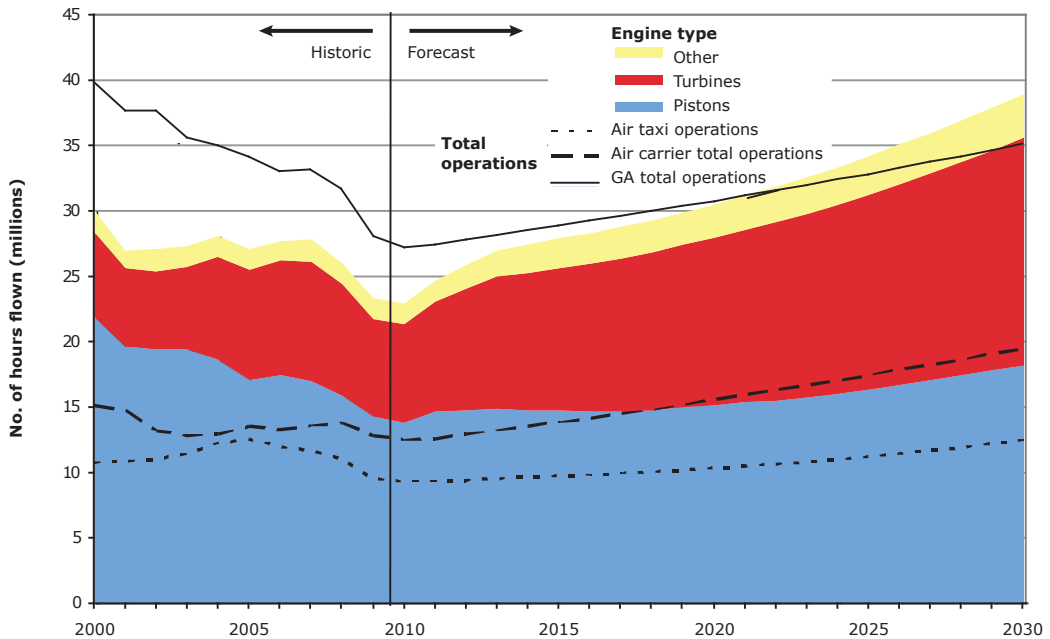
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Example 2: Fatalities and Aviation Safety. In another example, improved safety is a possible goal, but what safety data exist on air travel? These data would convey a sense of how significant the safety problems are and their nature. Do the safety data support significant additional research into safety, or has the United States achieved a level of safety that is sufficient given potential returns on investment and other competing demands?

As aviation use has increased, commercial air travel has remained relatively safe on a passenger mile basis (see Figure 3.4). In recent years, there have been fewer than 0.2 fatalities per billion passenger miles on commercial air travel, including air carriers, commuter carriers, and air taxis. By contrast, there have been nearly ten fatalities per billion highway passenger miles. However, general aviation has a much higher fatality rate—nearly 40 per billion passenger miles in the most recent year for which data are available—yet this has decreased by more than half in recent years.

Aviation safety failures have a measurable effect. For example, if we place the value of a lost life at approximately \$4 million and the cost of a seriously injured person at approximately \$212,000 dollars, then the average annual cost of lost life and injuries

Figure 3.3
General Aviation (GA) Hours Flown and Total Operations (2000–2030)



SOURCE: FAA (2009a), Tables 28 and 31.

NOTE: Data on operations count takeoffs or landings at airports (see FAA, 2009b, Appendix A).

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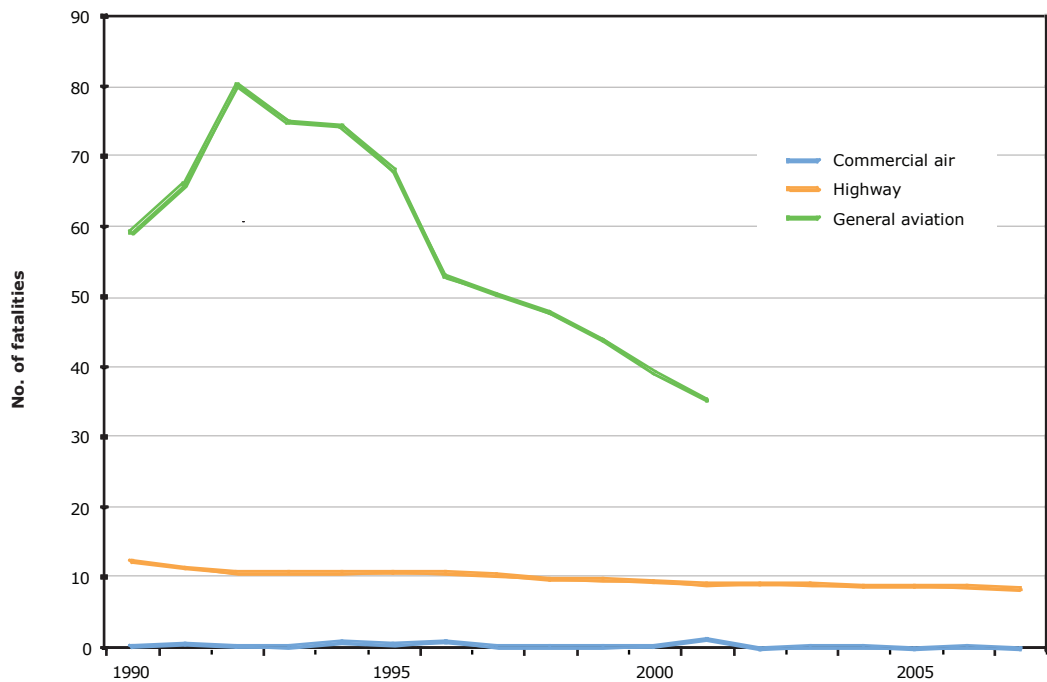
in U.S. aviation is approximately \$2.5 billion in social costs—nearly \$2.3 billion of which results from general aviation.

From a market perspective, commercial airline crashes result in a 1 to 3.5 percent immediate reduction in the equity value of an airline (Bornstein and Zimmerman, 1988; Chalk, 1986, 1987; Bosch, Eckard, and Singal, 1998).² The loss in equity value, which is not gained by other airlines, is much smaller than the total costs of a crash (Bornstein and Zimmerman, 1988).

Of course, it is difficult morally to place a value on the life of a human being, let alone such economic value as earnings potential, which varies widely by circumstances. Nevertheless, as we will discuss below, such estimates provide a quantitative way to compare aviation safety initiatives with other safety initiatives as well as to compare

² The 1 to 3.5 percent reduction in equity value measured by these studies is the instantaneous reduction in the stock price the day following an airline crash. If you make the assumption (which the cited papers do) that investors are rational and forward-looking, and that dividend payments reflect profitability, then this represents the instantaneous effect on profitability of a crash. Over time, the effect of past crashes on consumer demand and other factors that might affect an airline's profitability will dissipate, but we do not know at what rate. Other events that affect profitability also occur over time, and statistically it is not possible to differentiate the effect of a past crash from other events unless you look at the day immediately after a crash.

Figure 3.4
Number of Fatalities per Billion Passenger Miles, by Transportation Mode



SOURCE: Calculated by the authors based on BTS (2010a), Tables 1-37 and 2-1.

NOTES: Number of miles flown in the general aviation category is not available from 2002 onward. BTS data are currently available only through 2007.

RAND MG997-3.4

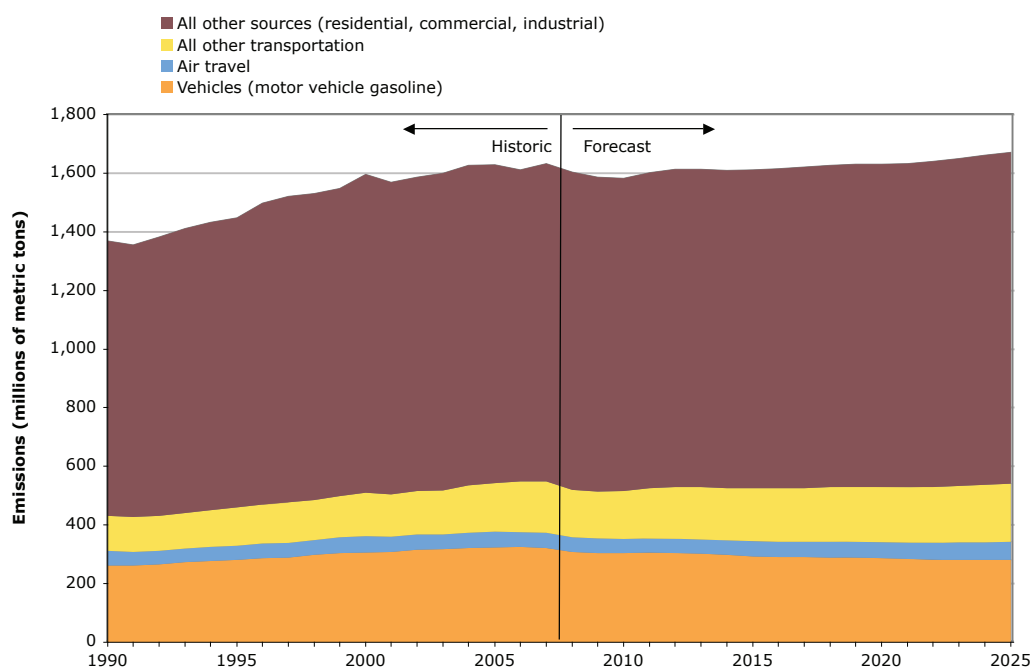
the costs of safety research candidates with the economic returns possible from such research.

Example 3: The Magnitude of Air Travel Carbon Emissions. As aircraft use has increased, it has also become cleaner. CO₂ emissions from aircraft have remained relatively steady since the early 1990s (see Figure 3.5). Altogether, air transportation produces about 3 percent of all carbon emissions in the United States; in coming years, it is projected to increase to 4 percent.³

On a passenger mile basis, air travel produces proportionally more carbon than driving does (see Figure 3.6). The most recent data indicate that aviation produced about 84 tons of carbon per million passenger miles and that driving creates about 65 tons per million passenger miles. Air travel carbon emissions have been decreasing on

³ NTS and BTS provided estimates in million metric tons of carbon. Where figures from other sources were provided in million metric tons of CO₂, we converted them to carbon using a ratio of 12.01 (the mass of one mole of carbon) divided by 44.01 (the mass of one mole of CO₂). If desired, tons of carbon can be converted to tons of carbon dioxide gas by multiplying by 3.667.

Figure 3.5
Total Carbon Emissions, by Source



SOURCE: Historic data are from BTS (2009a), Table 4-49; forecast data are derived from EIA (2009a), Table 19.

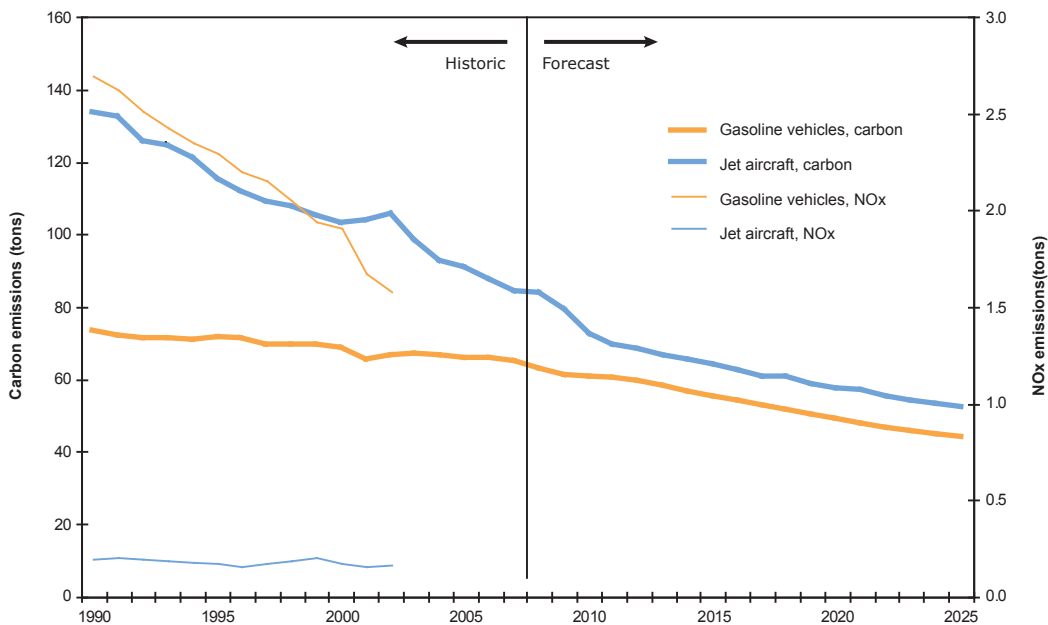
NOTES: BTS data are available only through 2007. One ton of carbon equals 3.667 tons of CO₂ gas.

RAND MG997-3.5

a passenger mile basis since 1990, when they were over 130 tons per million passenger miles. Carbon emissions from air travel and driving are both projected to continue falling in coming years. Altogether, air transportation accounts for just 12 percent of the CO₂ emissions resulting from transportation and 4 percent of all U.S. CO₂ emissions. Carbon emissions have likely remained steady in the face of increasing use of aviation because fuel efficiency has increased (see Figure 3.7). The number of miles flown per gallon in 2007 was nearly half again above its 1990 level, increasing from 0.29 to 0.43. As a result, total fuel consumption in 2007 was not much above its 1990 level, although it is projected to increase about 40 percent, or to about 23.3 billion gallons, by 2025.

In summary, carbon emissions from air travel do not represent a large, dominant source overall and the level of emissions per passenger mile has approached that of automobiles. Still, the need for carbon reductions overall naturally leads to the question, does air transportation offer competitive areas for reduction investments (see the discussion of options in Appendix B)? Also, fuel efficiency research would have a positive

Figure 3.6
Carbon and NO_x Emissions per Passenger Mile



SOURCES: Historic data are derived from BTS (2010a), Tables 1-32 and 1-37; (2008d), Table 4-14; (2009a), and Table 4-49; forecast data are calculated from EIA (2008), Tables 60, 65, and 67; FAA (2009a); and EIA (2009a), Table 19.

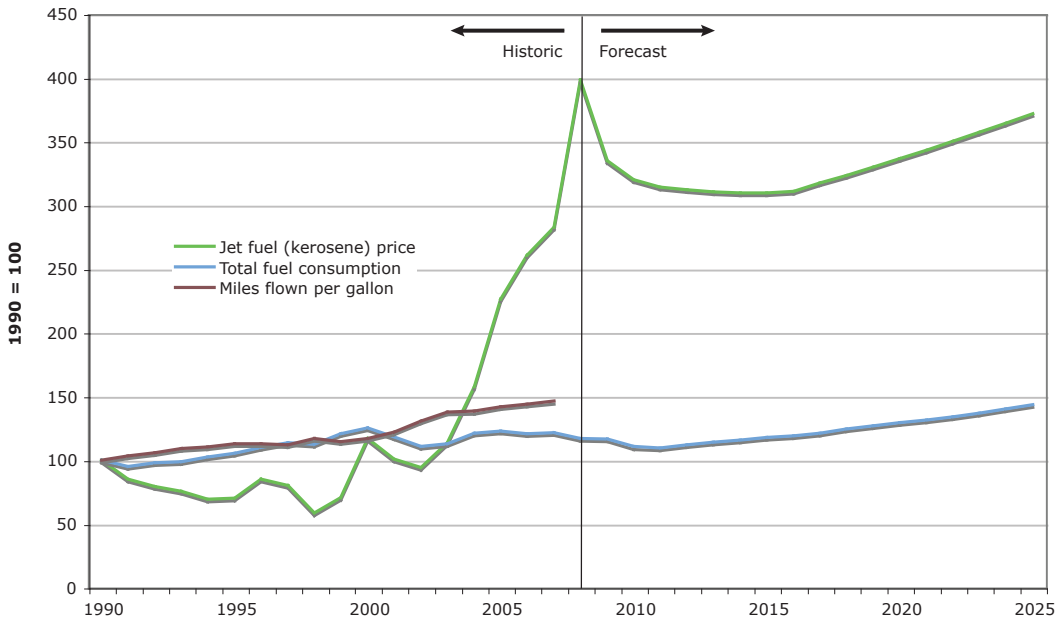
NOTES: The Environmental Protection Agency (EPA) no longer reports NO_x emissions for aircraft but includes them as part of “off-highway” transportation emissions. Therefore the NO_x emissions comparison cannot be updated. The historic data from EPA include all jet fuel consumption in one category. Using EIA’s forecasts that break out commercial air travel from military, we have assumed that 79 percent of jet fuel consumption and its associated emissions are from commercial air travel. One ton of carbon equals 3.667 tons of CO₂ gas.

RAND MG997-3.6

side effect of reducing carbon emissions, so a joint examination of those drivers with carbon-reduction needs would provide a useful perspective.

Example 4: Air Transportation Delays. Delays in the air transportation system have also been fairly steady in recent years (see Figure 3.8). They have fluctuated somewhat over time. For example, the share of on-time arrivals (i.e., flights arriving no more than 15 minutes later than scheduled) has increased from a low of 73 percent in 2000 to a high of 85 percent in 2002 but eroded again from 2002 to 2007. Weather accounts for most “post-pushback” delay (i.e., delay occurring after an aircraft leaves the gate). Airport terminal volume delays have decreased from more than 30 percent in 1990 to just more than 10 percent in 2007, whereas closed runways and taxiways accounted for less than 5 percent of such delays in 1990 but more than 10 percent in 2007. Flights canceled less than a week before scheduled typically account for less than 2 percent of delays, and diverted flights account for less than 0.2 percent of delays. Weather effects,

Figure 3.7
Trends in Aviation Fuel Consumption



SOURCES: Historic data are from BTS (2010a), Table 3-8, and BTS (2008c), Table 4-8; forecast data are calculated from EIA (2008), Table 66, and FAA (2009), Table 18.

NOTE: Figures for miles per gallon and fuel consumption are available in BTS only through 2007.

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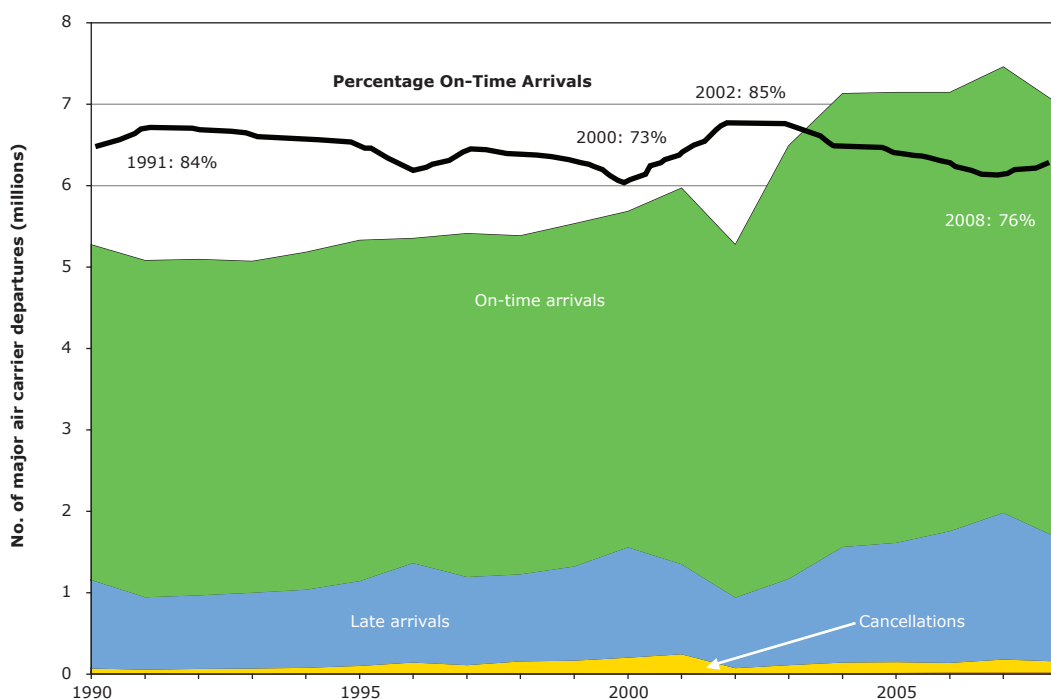
therefore, are important drivers of research into technological solutions that help to mitigate these effects.

Estimates of the costs of flight delays vary but are in the tens of billions of dollars. The Majority Staff of the Joint Economic Committee (JEC) of the United States Congress estimates that the total cost of domestic air traffic delays to the U.S. economy was about \$41 billion for 2007 (JEC, 2008). This includes consuming about 740 million additional gallons of jet fuel and 320 million passenger hours of lost time. The National Center of Excellence for Aviation Operations Research (NEXTOR) estimates the total cost at about \$39 billion for 2007 (Ball et al., 2010).

The portion of economic costs incurred by scheduled U.S. passenger airlines is estimated by the Air Transport Association (ATA) to be about \$61 per minute, or a total of \$6.1 billion dollars for calendar year 2008, which was 18 percent less than their estimate of \$7.4 billion for 2007 (ATA, 2010b). This estimate was less than half of the JEC's estimate (2008) of about \$19 billion and the NEXTOR estimate of \$16.7 billion (see Ball et al., 2010, for the NEXTOR estimate and for some discussion of the different methodologies used to produce these estimates).

Both estimates are about half the estimated costs of motor-vehicle traffic delay, which, for example, the Texas Transportation Institute estimates to cost \$78 billion

Figure 3.8
Trends in On-Time Arrivals and Flight Cancellations



SOURCE: BTS (2010a), Table 1-62.

NOTE: Data for 2009 are not available.

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annually through 4.2 billion hours in lost time and 2.9 billion gallons in wasted fuel (Schrack and Lomax, 2007).

As a result, air travel delays do have a sizable social cost, which some estimate at about \$40 billion per year. Thus, these drivers appear significant if viable solutions are available that have a reasonable ROI.

It is interesting to note that the government has made estimates of the value to consumers and business people of saving travel time. The valuation cost of delays on a per passenger hour basis is fairly low: about \$23 to \$40 per passenger hour (see Table A.1 and the adjoining discussion). Thus, reducing delays does not appear to offer strong economic benefits from technological solutions unless the costs are low in per passenger hour terms.

Balancing Competing Demands

The data above and in Appendix A point to several possible research themes. They also point to the need to balance possible aeronautics research efforts with several other public policy priorities.

For example, as we noted above, although aviation is extremely safe, aviation crashes still have an annual estimated social cost of more than \$2.5 billion. As a result, the National Aeronautics Research and Development Policy notes that aviation safety should be paramount and that “continual improvement of safety of flight must remain at the forefront of the U.S. aeronautics agenda” (NSTC, 2006). The National Plan for Aeronautics Research and Development and Related Infrastructure calls specifically for research to “enhance passenger and crew survivability in the event of an accident” (NSTC, 2007).

As the data we reviewed above show, the greatest social cost resulting from aviation safety failures is in general aviation—not commercial aviation. Furthermore, although commercial aviation accidents have become more survivable, with the accident fatality rate decreasing from 16 percent to 6 percent in recent decades, the general aviation accident fatality rate has remained at around 19 percent. Within general aviation, fatalities are also concentrated in certain ways. For example, one finding that pilots had among the most dangerous jobs in the United States also suggests that Alaska pilots are at particular risk, with a one-in-eight chance of dying during a 30-year career (Christie, 2003). General aviation accidents are also far more likely than commercial aviation ones to be the result of pilot error, with fire, weather, failure to use safety restraints, and off-airport location involved in many fatal accidents (see the discussion in Appendix B).

Such data indicate that research to improve aviation safety should consider focusing on general aviation, including developing solutions to prevent fatalities in accidents and addressing sources of pilot error. This might include ways to reduce the frequency and consequences of fire (e.g., fire suppression or aircraft structural changes), installation of airframe parachutes or other emergency landing systems, or ways to increase pilots’ situational awareness. In addition to training and regulatory differences, many of the safety problems of general aviation likely result from lower-cost aircraft, which have lower safety and design margins. General aviation (including rotorcraft) vehicle developers have relatively little research, development, test, and evaluation resources—implying that broader social benefits in general aviation safety could benefit considerably from public investment.

Policymakers need to consider not just where to focus aviation safety investments but how much to invest in aviation safety rather than other safety programs. For example, although the average number of aviation fatalities in recent years has been near 650, the average number of highway fatalities—and resulting social costs—has been almost a hundred times that, at 43,000. Policymakers might consider improving safety in other areas while focusing aviation investment where it would yield greater benefit than in other fields. However, such decisions need to reflect investments in those other areas as well as the ROIs in both areas.

Similarly, although air transportation is responsible for a large amount of CO₂ emissions, policymakers might consider focusing investments elsewhere to reduce

carbon emissions. U.S. aviation emits nearly 0.25 billion metric tons of CO₂ annually, resulting in a social cost of nearly \$3 billion (assuming a social cost of \$12 per ton⁴), but its emissions are only a small fraction of the nearly 1.2 billion tons of CO₂ emissions resulting from use of automobile gasoline, and the resulting \$14 billion in social costs. Also, aviation is a comparatively negligible contributor to emissions of other pollutants, such as carbon monoxide, nitrogen oxides, and volatile organic compounds. In addition, it may not be clear whether other research options besides fuel efficiency are as beneficial as non-aviation carbon offsets. For example, is the BCR for research and implementation of switching commercial jets to a noncarbon-based fuel better than the BCR for other carbon reduction concepts? As a result, policymakers may ask whether they should invest in other industries if they seek environmental improvements. It is critical to develop an objective decisionmaking process that asks these tough questions.

Limitations of a Purely Benefits-Driven Social and Economic Drivers Approach

There are limitations to the exclusive use of social and economic drivers for setting aeronautics research priorities.

First, economic estimates can be variable and approximate. Estimating an economic benefit is a function of inputs that are often market-driven. For example, the value of fuel savings depends on the cost of the fuel that is saved, but fuel costs have fluctuated widely in the past decade. Indirect economic benefits have even greater uncertainty. Although there is a consensus that aviation emissions (carbon and otherwise) contribute to global warming, the exact relationship between an additional ton of carbon in the atmosphere and the amount of global warming produced is unclear at best. The eventual cost to society of continued global warming is an issue of even greater concern. In addition to the limitations of social and economic analysis, a pure focus on drivers can overlook opportunities for which no current needs or markets exist. Research can create new needs and new markets as they creatively replace older ones, and predictions on the size of new markets are often unreliable.

Also, a pure focus on drivers ignores whether available technical ideas can make a significant contribution at a cost-effective level of investment.

This does not mean that the economic factors approach is without value. Simply put, the uncertainty needs to be addressed either by using the best estimates and noting their uncertainties or (better yet) by providing the range of economic estimates. Decisionmakers can then fairly weigh the importance of economic factors in their deliberations.

Other approaches that address vision, technical realities, and technical opportunities are described below, and these can complement the valuable lessons learned from analysis of drivers.

⁴ See the discussion in Appendix A.

Grand Challenges Approach (Vision-Driven)

We now consider a vision-driven approach where we motivate research on an identified concept that challenges the research communities to strive for something new that has significantly advanced capabilities.

A grand challenge is a fundamental problem in science or engineering, with broad economic and scientific applications.⁵ Grand challenges are useful paradigms in that they provide an easily understandable visionary objective that helps a community to understand and explore the space of the possible, motivate investments (public and private), motivate researchers who love a challenge, and focus research planning and execution on an objective. Examples of grand challenges in various disciplines include the following:

- Ansari X Prize for building a commercial spacecraft⁶
- replacement of wind tunnels with computational fluid dynamics⁷
- National Aerospace Plane
- artificial intelligence systems that pass the Turing Test⁸
- $P = NP?$ (i.e., finding a polynomial-time algorithm for any NP -hard problem)⁹
- the Defense Advanced Research Projects Agency Grand Challenge to construct a real-world autonomous vehicle
- true automatic target recognition
- universal natural language speech recognition
- weather forecasting for short- and long-term effects.

These examples show a range of types of grand challenge. Some are broad concepts that convey a general vision of an end point for a research community (e.g., true automatic target recognition). Others provide specific criteria for when the grand challenge will be met (e.g., the Ansari X Prize). Nevertheless, these convey useful visionary goals of meaning to the researchers in the various domains.

⁵ See, for example, the use of grand challenge concepts in OSTP (1987) and NSTC (1995).

⁶ The original Ansari X Prize was a competition to build a privately funded spacecraft that could carry three people and reach a suborbit of 100 km twice in two weeks (see X PRIZE Foundation, 2010).

⁷ Complete replacement of wind tunnels with CFD is difficult, for example, because of the lack of understanding of how to model complex turbulent flows.

⁸ The Turing Test is an experiment to answer whether a machine (computer) is intelligent. The goal is to answer the perennial question of whether humans can design and build intelligent machines (computers) (see Turing, 1950).

⁹ The Clay Mathematics Institute offers a \$1 million prize for the first correct proof of whether $P = NP$. This four-decade-old challenge is one of the most important unsolved problems in theoretical computer science. If you can quickly verify whether a potential solution is indeed a solution, can you also find a solution quickly to the posed problem? Here “quickly” means whether the time required is a polynomial function of the number of elements in the problem. See, for example, Fortnow (2009) for a discussion.

Grand challenges can be pursued at different maturity and granularity levels to achieve broad overarching visions and to provide interim goals at somewhat lower levels of maturity along the path toward a vision, application, or technology.

Sometimes, developing a large-scale goal can spawn many different research projects, some of which will eventually lead to results. NASA took this approach when President John F. Kennedy announced that the United States would pursue a program to land a man on the moon and return him safely to earth. This “grand challenge” to the nation contained no specific research or projects. Instead, it was left to those tasked with meeting the challenge to develop a plan, execute it, and accomplish the goal. Although the United States was ultimately successful in landing a man on the moon and returning him to earth, many of the research projects required to accomplish the goal also spawned other goals of their own.

In this same spirit, NASA ARMD could develop a series of grand challenges that might spawn many different research projects while attempting to accomplish a large goal. To this end, if the grand challenge is never accomplished, the results of the research could still produce useful progress and results, depending on the challenge proposed, the quality of the investment decisions, and the size of the investments.

This approach has the benefit of allowing creativity to enter the decisionmaking process. Although they are often qualitative, useful grand challenges will be attractive, capturing the national interest and creating public backing.

Given practical limitations, the nation will benefit most from focusing on a very small number of grand challenges in its public aeronautics investments. This would reflect pressures on the federal budget and make the most of the resources currently devoted to aeronautics research. Having a relatively small number of such challenges could also help each effort’s chance of success and could build substantial groundwork for future advances.

Identifying and Selecting Grand Challenges

Grand challenges can provide a broad, overarching vision of research that lends itself to different levels of research maturity, including basic research, applied research, and the development of technology, platforms, and systems. This means that grand challenges can and should have underlying research themes and technical goals.

Grand challenges need to be explicit about the current and future context, priorities, and broad demands. Likely future conditions and constraints on grand challenges include the national aeronautics R&D policy (NSTC, 2006) and the limited resources available to NASA (while allowing for the possibility that an exciting grand challenge with considerable potential could attract additional funding).

Developing and selecting grand challenges will require prioritizing or weighting inputs from various stakeholders. Of course, stakeholders approach research investment decisionmaking in ways that reflect their own relationships to the end results. Each will also have differing focuses, approaches, and selection criteria for investing

in aeronautics research (see Table 3.1). Public policymakers are interested in social goods as well as the needs of their own bureaucratic functions. The military is focused on warfighting missions. The business community is focused on financial returns for their company. And, finally, academics and other researchers are motivated to obtain funding for their research. Therefore, the overall objective for U.S. aeronautics research should dictate who should be asked to provide input to the research portfolio decision-making so as to align the results with the overall objectives. For example, if research is intended to address political, public, or regulatory issues (or needs arising from them), then policymakers and broad public and industry considerations should have the greatest weight. These stakeholders are likely to favor new, exciting research projects that can yield broad societal benefits. If research is intended to benefit the user community, then user industry considerations should have the greatest weight. Military users are likely to favor projects that yield useful products supporting warfighters, and businesses are likely to favor those providing competitive advantages to the industry and yielding high ROIs. If research is focused on technical advances, then aeronautics experts should have the greatest say. Academic researchers are likely to favor processes with open competition, ideally to pursue novel ideas. Still other stakeholders will have their own, varying reasons for wishing to see investments in aeronautics research.

Public research plans have typically focused on technological achievements and broad social benefits. They generally have not included a thorough, explicit assessment of social net benefits and problem rankings, the evolving regulatory environment, future uncertainties and risks, objective frameworks for selecting among competing R&D efforts, market conditions and adoption, spending requirements to bring a project to maturity, and when and how much the private sector should be

Table 3.1
Types of Stakeholders and Their General Focus and Approaches to Investment Decisionmaking

Stakeholder Type	Focus (Reasons for Investing)	Common Approaches to Making Investments	Example Selection Criteria
Policymakers and the public at large	Applied science for social benefits and exciting visions of the future	Set grand challenges and focuses based on public appeal and social issues	National prestige, public objectives/good, gross domestic product, trade balance, good for nation as a whole
Military community	R&D; production	Warfighter requirements-driven	Value to warfighter (mission-based)
Business community	Development; competitive advantages	Business models for converting opportunities to profits	Business opportunities; ROI; good for company
Academics and the research community	Basic and applied science	Give money to the researchers and let them fight over it	Originality; interesting problem; advances the state of knowledge

involved. These are the additional areas that our analysis seeks to help NASA and interested policymakers address.

We turn next to analysis of some current and prospective issues likely to affect U.S. industry, including some approaches to address them and a discussion of how they might shape a framework for identifying and addressing grand challenges.

Different Ways to Generate Candidate Grand Challenges

Grand challenges can be generated in a number of ways—in isolation or together. The government could solicit ideas in a formal public request for information. Scientific and technical community panels could be established to brainstorm and vet ideas. Government research leaders, policymakers, and political appointees could promote their own priorities by designating challenges that interest them. Research studies could be established to examine drivers, topical areas, and brainstorm candidates and to prioritize those candidates.

These approaches could be developed top-down from drivers or new concepts (a “driver pull” approach). Conversely, they could be developed based on bottom-up technical ideas or opportunities (a “technology push” approach). A combination of both approaches would produce a richer set of candidates for consideration and evaluation while providing grounding by employing both perspectives together.

The evolving national aeronautics R&D plan (NSTC, 2007, 2008 2010) offers one mechanism both to identify grand challenges and to balance competing challenges. The plan specifies several goals, built on the principles of U.S. aeronautics policy, detailing goals in the near term (less than five years), mid term (five to ten years), and far term (more than ten years). The specified goals reflect a consensus of the Aeronautics Science and Technology Subcommittee of the National Science and Technology Council, comprising members of several federal agencies, as well as input from nonfederal stakeholders. Achieving them all will require deep and sustained fundamental research. Some of these goals can be accomplished by civilian agencies; others are more appropriate for military research. Determining how ARMD can best support them will require placing them within the context of grand challenges that NASA has the mandate and resources to identify and support.

Grand Challenges Concept Projects

Our study team brainstormed a set of illustrative aeronautics grand challenges that the country might consider as a way to explore what aeronautics research might pursue, especially in the long run. Table 3.2 lists those candidate grand challenges that we felt were the most reasonable—grouped loosely by the areas addressed in the National Aeronautics R&D Policy (NSTC, 2006). Further analysis would be required to identify the viability of these grand challenges and their relative importance to decisionmakers.

Table 3.2
Illustrative Aeronautics Grand Challenges and Themes

Policy Principal Areas	Possible Grand Challenge
Safety	Maintain passenger safety levels as the industry moves from aluminum to composite airplanes Make general aviation as safe as commercial air travel
Environment	Planes as fuel efficient as trains “Silent” airplane Zero greenhouse-gas emission plane (hydrogen plane?)
Airspace	Triple passenger air transport system throughput Unmanned vehicles in U.S. civil airspace
Reduced travel time	Green, quiet, supersonic flight at transonic prices
Increased travel comfort	<i>(none—problem not dominated by technology)</i>
Convenience	Safe personal air vehicles
Space access	Practical air-breathing space-access vehicles
National security	Month-long (or even year-long) loitering surveillance aircraft Automated unmanned aircraft Hypersonic global-strike vehicle Unmanned vehicles in U.S. civil airspace Cost-effective military vertical envelopment transport vehicles

NOTES: Vertical envelopment is a “tactical maneuver in which troops, either air-dropped or air-landed, attack the rear and flanks of a force, in effect cutting off or encircling the force” (DoD, 2010). See, for example, Grossman et al. (2003) for a discussion of this concept and its technical and logistical challenges.

Limitations of the Grand Challenges Approach

Sole use of the grand challenge approach to setting research goals without input from other approaches has some limitations.

One can easily generate a large number of grand challenges, but many may be too idealistic given current technology (e.g., may be achievable only after tens if not hundreds of years), ungrounded in physical reality (e.g., defy the laws of physics), lack compelling social or economic support, or fly in the face of major known technical roadblocks.

Grand challenges can be very ambitious and may never be achieved even if significant progress is made. Thus, care needs to be taken to use grand challenges as a motivator and not necessarily as the definitive measure of success at the end.

Grand challenges may require large resources (especially financial) not viewed by stakeholders as commensurate with the value of the ultimate end. They may also

require these resources over a very long time—even beyond the tenure of the original supporters of the grand challenges. If grand challenges are changed often, then small bits of progress may be made along the way without achieving major objectives.

Thus, grand challenges in isolation may have consequences in reducing resource commitments to other areas; failure of high-profile efforts produces bad publicity and reduces public trust, and benefits are hard to establish when making the initial case for the effort.

In combination, however, we suggest below that grand challenges can be a useful tool in the hands of policy planners trying to excite and reinvigorate aeronautics.

National R&D Policy Guidance Approach (Directive-Driven)

A third approach is one simply driven by directive from above. In the case of aeronautics, we now have a new National Aeronautics Research and Development Policy (NSTC, 2006) and a National Plan for Aeronautics Research and Development and Related Infrastructure (NSTC, 2007, 2008, 2010) that could be used to direct research activities across the government.

Of course, individual agencies and departments have additional considerations that pertain to their own situation. These include their current mission, broader strategic plans, budgetary constraints, congressional mandates, etc.

As with the national policies and plans, agency-specific philosophies and values can also help to guide strategic planning processes. For example, what level of technical maturity should be supported? How integrative should the efforts be on the system level? Should demonstration vehicles be supported?

These can be drivers for strategic options but will not by themselves define the aeronautics R&D that should be supported.

Limitations of the Directive-Driven Approach

One might ask whether NASA and other governmental entities can or should simply implement those policies and plans. Unfortunately, that perspective is too simplistic for a number of reasons.

First, although aeronautics policy helps to resolve a number of perennial debates (such as the role of the U.S. government in advancing research that aids U.S. commercial companies), the policy itself does not indicate what specific R&D activities should be pursued. Rather, it sets out a broad policy and motivation for such research.

Second, the R&D plans are not directive in the sense that they are not exhaustive and do not limit what departments and agencies should consider doing. Each entity must reflect on the plan relative to its missions, priorities, and available resources. Also, the plans do not come with budgetary authority, so each entity still grapples with its research agenda within its usual managerial and budgetary channels.

Finally, the R&D plans are not directive in the sense that they are constructed by the very agencies and departments in the government that implement the plans. Thus, in some sense, these plans paint a broad picture of existing plans and priorities rather than providing guidance that sets those priorities. Calling them “directive” is a self-fulfilling proposition until those plans become truly driven by broader consideration of national objectives independent of ongoing activities.

That is not to say that these plans serve no useful purpose. Indeed, they provide a valuable picture of what the government thinks is currently important, contributing information to the public debate on what the government should be doing. These plans also serve a coordinating function by bringing the agencies and departments together, sharing views and constructing a government-wide vision and plan.

Thus, the national policies and plans are an important factor to consider when setting one’s research agenda, but by themselves they do not provide a stand-alone exhaustive answer of what research portfolio to pursue.

Science- and Technology-Driven Approach (Idea- and Opportunity-Driven)

A fourth approach based on S&T inputs from SMEs also can be considered. This approach uses technical ideas and opportunities from the research community to identify the range of possibilities. Their perspectives would be instrumental in implementing the strategy.

Research Ideas from the National Academies

The NRC’s Aeronautics and Space Engineering Board (ASEB) reviewed civil aeronautics for NASA to provide recommendations from the technical community on what research NASA and the nation should be doing (NRC, 2006). This “decadal survey” provided extensive discussion of possible research activities across the entire range of civil aeronautics. As part of this activity, the research members executed a prioritization exercise that resulted in their identification of 51 challenges that they felt were the most important to pursue. Table 3.3 lists these challenges grouped by the research and technology areas used in their study.

Although this input is extensive and cross disciplinary, the ASEB’s prioritization methodology did not incorporate the broader scope of considerations discussed in our process. The ASEB process also used a nonlinear rating system that introduces anomalies when manipulated arithmetically to obtain a final score for each research topic. In addition, having researchers rate their own research areas risks introducing bias in the scoring. Still, the decadal survey is a valuable input to the process and provides an extensive consideration from the technical community on research topics to consider.

Table 3.3**Decadal Survey's 51 Highest-Priority Challenges for NASA Aeronautics, by Research Area**

A: Aerodynamics and Aeroacoustics
<p>A1 Integrated system performance through novel propulsion–airframe integration</p> <p>A2 Aerodynamic performance improvement through transition, boundary layer and separation control</p> <p>A3 Novel aerodynamic configurations that enable high-performance or flexible multimission aircraft</p> <p>A4a Aerodynamic designs and flow-control schemes to reduce aircraft and rotor noise</p> <p>A4b Accuracy of prediction of aerodynamic performance of complex 3-D configurations, including improved boundary-layer transition and turbulence models and associated design tools</p> <p>A6 Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing</p> <p>A7a Aerodynamic configurations to leverage the advantages of formation flying</p> <p>A7b Accuracy of wake vortex prediction and vortex detection and mitigation techniques</p> <p>A9 Aerodynamic performance for V/STOL and ESTOL, including adequate control power</p> <p>A10 Techniques for reducing/mitigating sonic boom through novel aircraft shaping</p> <p>A11 Robust and efficient multidisciplinary design tools</p>
B: Propulsion and Power
<p>B1a Quiet propulsion systems</p> <p>B1b Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments</p> <p>B3 Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits</p> <p>B4 Improved propulsion system fuel economy</p> <p>B5 Propulsion systems for short takeoff and vertical lift</p> <p>B6a Variable-cycle engines to expand the operating envelope</p> <p>B6b Integrated power and thermal management systems</p> <p>B8 Propulsion systems for supersonic flight</p> <p>B9 High-reliability, high-performance, and high-power-density aircraft electric power systems</p> <p>B10 Combined-cycle hypersonic propulsion systems with mode transition</p>
C: Materials and Structures
<p>C1 Integrated vehicle health management</p> <p>C2 Adaptive materials and morphing structures</p> <p>C3 Multidisciplinary analysis, design, and optimization</p> <p>C4 Next-generation polymers and composites</p> <p>C5 Noise prediction and suppression</p> <p>C6a Innovative high-temperature metals and environmental coatings</p> <p>C6b Innovative load suppression and vibration and aeromechanical stability control</p> <p>C8 Structural innovations for high-speed rotorcraft</p> <p>C9 High-temperature ceramics and coatings</p> <p>C10 Multifunctional materials</p>
D: Dynamics, Navigation, Control, and Avionics
<p>D1 Advanced guidance systems</p> <p>D2 Distributed decisionmaking, decisionmaking under uncertainty, and flight-path planning and prediction</p> <p>D3 Aerodynamics and vehicle dynamics via closed-loop flow control</p> <p>D4 Intelligent and adaptive flight-control techniques</p> <p>D5 Fault-tolerant and integrated vehicle health management systems</p> <p>D6 Improved onboard weather systems and tools</p> <p>D7 Advanced communication, navigation, and surveillance technology</p> <p>D8 Human-machine integration</p> <p>D9 Synthetic and enhanced vision systems</p> <p>D10 Safe operation of unmanned air vehicles in the national airspace</p>

Table 3.3—continued

E: Intelligent and Autonomous Systems, Operations and Decisionmaking, Human Integrated Systems, Networking and Communication
E1 Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems
E2 New concepts and methods of separating, spacing, and sequencing aircraft
E3 Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems
E4 Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence
E5 Interfaces that ensure effective information-sharing and coordination among ground-based and airborne human and machine agents
E6 Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system
E7 Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts
E8a Transparent and collaborative decision support systems
E8b Using operational and maintenance data to assess leading indicators of safety
E8c Interfaces and procedures that support human operators in effective task and attention management

SOURCE: NRC (2006).

NOTE: V/STOL, vertical and/or short takeoff and landing; ESTOL is extremely short takeoff and landing; ATM is air-traffic management.

Limitations of the Science- and Technology-Driven Approach

SMEs are by definition knowledgeable on the issues, but they are also likely to be biased toward their areas of expertise. They will naturally emphasize the importance of technologies that they understand, while neglecting other concepts that are not in their chosen discipline.

Additionally, the issue of enlightened self-interest and potential conflicts of interest needs to be addressed. The community of aeronautics SMEs is not that large. A continuing problem for NASA is that a large fraction of aeronautics SMEs resides within their own organization. Many would argue that NASA is the greatest source of aeronautics expertise in the United States, but obvious conflicts of interest develop when using that talent pool to evaluate government research priorities. However, turning to industry or academia for input is not a panacea either. The U.S. aeronautics industry is both the consumer of NASA aeronautics research and a contractor to NASA for technology development. Its goal would be to have NASA develop technologies that improve the industry's bottom line or competitiveness rather than the greater social good—efforts that benefit both are obviously a win/win and the easiest to justify (see the theoretical discussion of public and private investments in Chapter Two). Then, if possible, industry researchers might be motivated to convince NASA to contract the research effort back to them. Finally, aeronautics research in academia is certainly supported in part by grants from NASA. As SMEs, they also tend to support further investments in fields that their own research programs are likely to benefit from.

In addition, basic research generally offers a potential benefit, but it is very hard to determine in advance the exact cost of a completed research theme given all the uncertainties inherent in research.

This is not to suggest that a technically driven approach is without value. The evaluation of aeronautics research priorities by nonexperts would be less biased, but, unfortunately less informed by the state of the art and the range of the practical (or even the possible). Still, by using structured processes, the objectivity of individual inputs can be improved (e.g., through the mechanisms of cross-checking other domains and driving for explanations of technical risks and uncertainties). Also, technical concept development practices can be organized in a fashion to limit any anticipated direct benefits or to strive for consensus across the competing interests. In addition, SMEs—especially when industry developers are included—should have a rough sense of the risks and uncertainties involved in different technical approaches, the scope of current and remaining RDT&E to be done, and the practical barriers to implementation and exploitation.

However, the best way, perhaps, to improve technical inputs is through a combination of the four approaches outlined.

Combining the Approaches

Each approach has its strengths and weaknesses; a combined process that employs each approach has the benefit of employing some of the benefits of each while mitigating their weaknesses through the complementary employment of other approaches. The decision framework discussed in the next chapter provides one such process.

A Multidimensional Decision Framework for Prioritizing Aeronautics Research

Despite all the vision and desires, resources available for aeronautics research (or any research for that matter) are always limited, so priorities must be established. These pressures to prioritize decisions become especially evident and are more likely to be contested in times of declining budgets. As detailed in Chapter Two, decisionmakers have decreased NASA's aeronautics R&D funding since the mid-1990s by about two-thirds to 2.7 percent (\$507 million)¹ of NASA's total budget of \$18.7 billion in 2010 (NASA, 2010a). As a result of this trend, NASA has been forced to reduce, refocus, and reorganize the aeronautics research effort in ARMD. ARMD has done so by prioritizing fundamental research over demonstrators and focusing on maintaining its broad aeronautics research workforce and capabilities as much as possible. However, it has become evident to various stakeholders, including policymakers, industry, and academia, that the reduced resources have led to a reduced capacity for conducting aeronautics research, and those stakeholders are naturally concerned with how NASA determines what its priorities are.

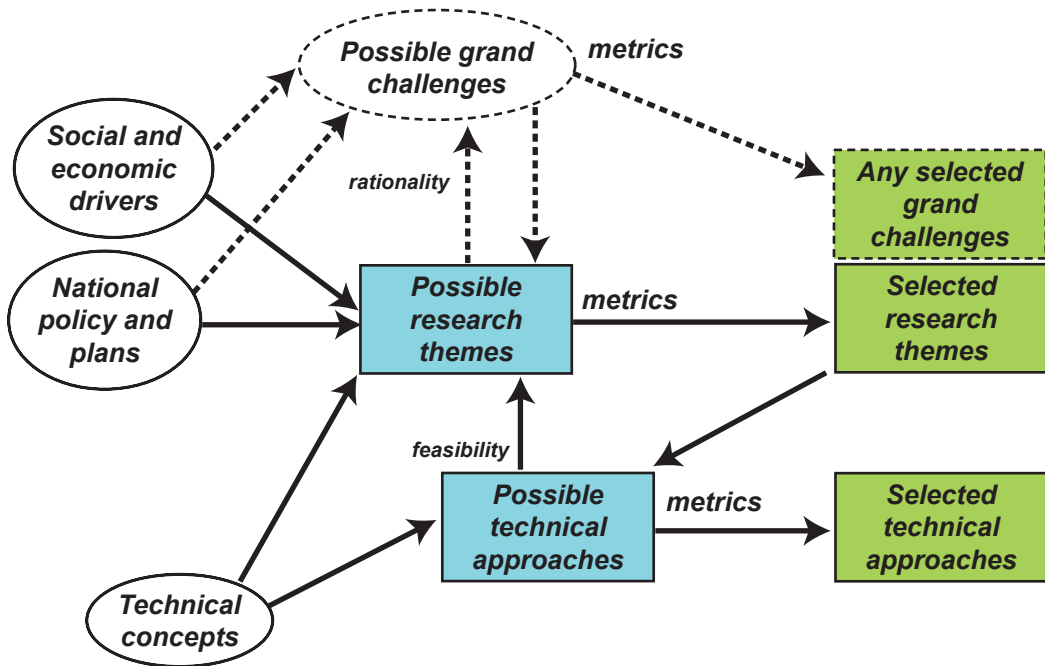
In the last chapter, four approaches for prioritizing research efforts were described and discussed. In reviewing the limitations of each, the obvious conclusion is that no one approach is preferable for prioritizing ARMD's research plan.

In this chapter, we describe a decision framework that combines these approaches to prioritize and select research themes, identify underlying technical approaches for addressing those themes, and prioritizing among those approaches and subordinate approaches. This combined framework also allows us to identify and consider complementary research activities that may help to address multiple objectives.

Figure 4.1 shows a basic flow chart of how these approaches (in ovals) relate and support one another in such an integrated framework. The decision framework involves a number of steps:

¹ As discussed briefly in Chapter Two, current program budgets are not burdened by CM&O "taxes," so the actual equivalent budget and percentage are slightly higher when compared to years in the 2000s and before.

Figure 4.1
Flow Chart for Combining Strategic and Technical Approaches to Guide Aeronautics Research



RAND MG997-4.1

- examination of national policies and plans
- examination of social and economic drivers
- generation of grand challenges (optional)
- generation of related research themes
- prioritization of research themes and any grand challenges using strategic metrics
- generation of underlying *technical approaches*
- prioritization of technical approaches using programmatic metrics.

As we will discuss below, the technical approaches are the basic ways that we can address the goals of the research themes, not detailed technical challenges.

We use research themes and technical approaches as intermediates between top-level strategic priorities and more detailed research activities. We found it important to have such intermediaries to facilitate the application of strategic prioritization metrics while controlling the multiplicative growth of the process. For example, early in our study, we found that NASA was funding over 600 individual research efforts. It would be very difficult, time-consuming, and not very meaningful to apply, say, 20 high-level strategic metrics to all those efforts because it would involve over 12,000 applications

of a metric to a project (e.g., a table with 600 rows and 20 columns). By combining those efforts into related research themes, we could apply the metrics in our analysis to the research themes to decide what would make sense to pursue at the strategic level. The themes in turn provide strategic support to the underlying research efforts within each theme, allowing us to evaluate them as a group rather than individually.

Note that using grand challenges can be a useful and motivational step, but they are not necessarily required to generate research themes; research themes by themselves that map back to policies, plans, and drivers provide solid justification and logical selection bases for their themes and the underlying technical approaches and research that support those themes.

In this chapter, we will illustrate how such a framework can be employed through the use of notional but informed examples.

Developing Grand Challenges

Chapter Three discusses ways and considerations for developing grand challenges. Moreover, in that chapter, Table 3.2 lists potential grand challenges that we found to be a reasonable set for discussion purposes, judging by our analysis of aeronautics research drivers and technical reasonableness, which includes the data and perspectives given in the appendices. The product of much internal debate on our project team, these grand challenges reflect some practical aspects that would make them more implementable or provide broader benefits. For example, we qualified supersonic commercial flight with the additional objectives of making it “green” (to force consideration of environmental effects), quiet (to deal with the problem of sonic booms over land), and at transonic prices (to force a consideration of cost so that ticket prices would be low enough to prevent supersonic flight from remaining a niche market).

Developing Research Themes

Research themes are focus thrusts that provide research areas that can be evaluated using strategic metrics. Having a higher-level theme is important to enable consideration of relevancy and transparency of research. Without this higher-level grouping, we found that more specific research program activities become too numerous and detailed to effectively address as a whole, are often too technical to explain to nonspecialists, and are too far from the kind of strategic metrics that are important to map back to broader social drivers and strategic policies and plans.

The importance of relevancy in planning applied research activities is self-evident, although the process of determining it is complicated. If the results of the research are

not relevant to a goal or driver, then we are relegated to research for research sake—a much less supportable position if the intent is to connect the applied research to a goal.

Note that early in the process, the strength of relevancy in selecting candidates to consider should not be overly restrictive, because the assessment and resource-commitment stages will weed out less-relevant research efforts. In other words, it is useful to show decisionmakers a wider set of potential research themes so that they can see not only the final set of selected options but also the candidates that were not funded.

Transparency in the decision process is equally (or perhaps more) important. In the end, decisionmakers will have to justify their decisions to fund or not fund research to the various stakeholders of aeronautics research: the public, their representatives in Congress and the White House, industry, academia, and even researchers in and out of the government. Transparency is vital to this justification. Otherwise, decisionmakers see only lists of approved activities, making it hard to get a sense of the range of options.

Research Themes Should Be Neither Too Broad Nor Too Technical

Research themes need to involve a concept that can be explained to a managerial superior, a member of the public, or a Capitol Hill staffer in little more than a paragraph. They cannot be too broad or too technical.

Not Too Broad. Simply listing a speed-regime of aircraft (such as supersonic) or an application area (such as aviation safety) is too broad. It is very difficult for decisionmakers to compare the benefits of such broad topics, and areas such as safety seem valuable by default unless we can identify more specific concepts for which values and ROIs can be estimated.

Also, getting the level right is important for prioritizing between themes. Is aviation safety research more or less important than supersonic aeronautics research? Inability to answer that question is inherent in the question itself and the broadness of the themes.

It is also very difficult to judge progress on a theme against the resources provided without more specificity.

Themes should also be something that a decisionmaker would at least consider denying funding for. It is unlikely that a decisionmaker would ever recommend zero research dollars for aviation safety generally. Instead, budgets would be reduced, but the stakeholders would never know exactly what technologies they are forgoing with those reductions.

Not Too Technical. On the other hand, research themes should not be so narrow or detailed that only experts can interpret and understand them. Returning to the supersonics research example, developing realistic sonic boom propagation models or improving supersonic jet noise models validated on innovative nozzle concepts is very technical. This makes such examples hard to evaluate and understand why they might

be important. In contrast, a research theme of economical commercial supersonic flight over land is a concept that the public can grasp and evaluate the importance of and commit appropriate resources to. Once such a theme is established and evaluated, NASA researchers can in turn determine at a later date how much of available resources needs to be committed to sonic boom propagation models for advancing sonic boom mitigation or to improving supersonic jet noise models for innovative nozzle concepts to achieve the ultimate goal of commercial overland supersonic flight.

Just Right. The list of candidate research themes should be broad enough to demonstrate major research areas yet narrow enough to facilitate consideration and analysis. A list of two to three dozen research themes would give decisionmakers a healthy set of options for debate without impeding expediency. In other words, if there are too few themes and all of them are funded to some degree, it is then unclear what research is not being funded. Too many themes, of course, make the task overly complicated and possibly overwhelming. Just right is enough research themes that if, say, 10–20 percent of them are unfunded over a period of years, NASA’s inherent research capabilities are not threatened and stakeholders are aware of exactly what is and is not being funded.

The following list illustrates some possible research themes that we developed after examining current drivers, national policies and plans, and potential grand challenges. This list is not meant to be exhaustive; rather, it demonstrates a reasonable starting point for future discussions, according to our reading of the literature, our discussions with researchers, and our internal debates. These research themes are discussed in more depth in Appendix B, but here is a short explanation of each. Having unmanned aerial vehicles (UAVs)² in civil air space refers to the challenge of being able to handle UAVs in the national air space (NAS) at the same time as commercial and general aviation vehicles. The entries “2x–3x” pose different ways to double (2x) or triple (3x) the airspace capacity: increasing airspace capacity, increasing airport capacity, shifting air traffic to less-congested times, and increasing the size of aircraft for the same number of flights to increase passenger throughput. To develop “green” aircraft, we need to focus on technologies that make vehicles quieter, more fuel efficient, and less polluting. The revolutionary airplanes are to explore fundamentally new shapes for airplanes; here “N” refers to current generation vehicles, N+1 (not listed) are new vehicles using existing research advances, N+2 are blended-wing-body (BWB) vehicles, and N+3 are the next promising concepts to be determined. Large transport aircraft that offer either vertical takeoff and landing (VTOL) or short takeoff and vertical landing (STOVL) capabilities could be advanced to pursue such concepts as vertical envelopment or aerial construction cranes. Wide-scale civil airspace rotorcraft refer to the concept of improving the noise, safety, and efficiency of rotorcraft to enable their expanded use in civil passenger transportation (e.g., for suburban or rural airports).

² UAVs are also known as remotely piloted vehicles (RPVs) and—when considered with supporting systems—unmanned aircraft systems (UASs).

Green and safe rotorcraft relate to the prior theme but without the focus necessarily on civil passenger transportation. General aviation airplane safety involves examining new concepts that can improve the safety of private airplanes, jets, rotorcraft, light sport, and experimental aircraft. Maintaining commercial aviation safety levels refers to research that ensures that safety does not deteriorate given the introduction of various new vehicles and technologies (e.g., the trend to increased use of composite rather than aluminum structures; changes in the air traffic control system; changes in vehicle controls). Supersonic flight over land refers primarily to addressing sonic boom issues that currently preclude such flights because of public complaints about the noise. Air-breathing hypersonic space access and missiles refer to the continued development of such vehicles that use atmospheric air (e.g., in ramjet and scramjet engines) rather than vehicles that carry oxygen for combustion in the air. Space reentry involves research to address deceleration and controlled flight on earth or other planets. Finally, the systems approach theme is a higher-order approach to integrate breakthroughs in individual areas with the hope of achieving greater vehicular capabilities (e.g., exploring different jet engine locations to both improve performance and reduce noise).

Some Possible Aeronautics Research Themes

- UAVs in Civil Airspace
- 2x-3x: NextGen Airspace: increased airspace transport throughput
- 2x-3x: NextGen Airportal: increased airport throughput
- 2x-3x: Time-shifting management
- 2x-3x: Efficient large aircraft
- “Green” aircraft
- Revolutionary airplanes: blended-wing body (N+2)
- Revolutionary airplanes: future (N+3)
- STOVL or VTOL large transport (vertical envelopment/aerial crane)
- Wide-scale civil airspace rotorcraft
- Green and safe rotorcraft
- General aviation airplane safety
- Maintain commercial aviation safety levels
- Supersonic flight over land
- Air-breathing hypersonic space access
- Air-breathing hypersonic missiles
- Space reentry
- Integrate breakthroughs across vehicle in a systems approach.

Developing Technical Approaches

Within each research theme, we need to ask what basic technical approaches should be selected for pursuing the objectives of the research theme. Because we are still dealing

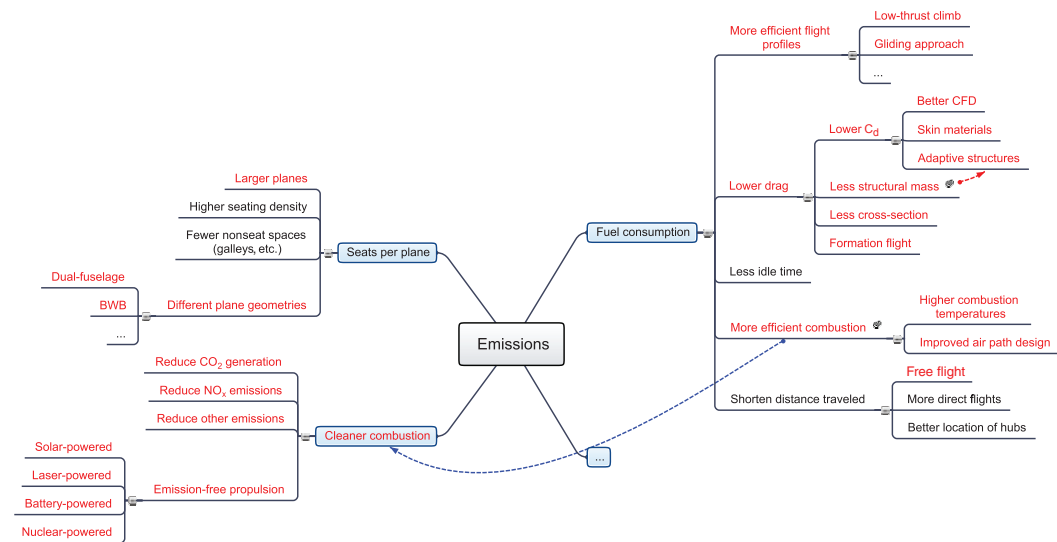
with strategic planning, we want to keep the technical discussion at a relatively high level. This allows policymakers and decisionmakers to engage and oversee the choices of technical approaches, providing insight into a range of considerations such as the availability of technical ideas, their associated risks and maturity, the costs involved in each, and whether multiple approaches are or should be considered to mitigate risks.

Consider, for example, the potential research theme of producing a greener aircraft. Here “green” implies a more environmentally friendly vehicle. A major aspect of making aircraft greener is to lower emissions. Figure 4.2 shows a breakdown of logical technical approaches to reducing aircraft emissions. At the first level, we could pursue research into cleaner combustion, changing the number of seats per airplane to reduce emissions per passenger mile, or reducing fuel consumption. Each of these approaches in turn can be decomposed into lower-level approaches, as illustrated by the decomposition in the graph. The figure illustrates a decomposition of the goal of reducing aircraft emissions by iteratively showing different approaches that might be taken to achieve a goal and underlying subgoals and approaches. Here, we used our expert judgment of the challenge box in the center and decomposed it into the basic options of changing the number of seats per plane (to reduce emissions on a per passenger basis), cleaner combustion (on the lower left), reduced fuel consumption (which often reduces emissions), and a placeholder link in the lower-right to additional, unexpanded options. Each of these basic approaches is in turn broken down by following the tree below it. So, for example, reduced fuel consumption could be achieved through more efficient flight profiles in the NAS, lower vehicular drag, less idle time on the airport tarmac, more efficient combustion, and shortening the overall travel distance. Related areas are shown with arcs (such as the relationship between more efficient combustion on the right and cleaner combustion on the left). We highlighted in red text areas for which we concluded that aeronautics research could make a significant contribution to that goal or approach.

Some judgment needs to be taken to pick an appropriate level of detail for consideration. Consider, for example, the decomposition of the goal of reducing fuel consumption. The upper-right section of Figure 4.2 shows that pursuing fuel consumption savings through more efficient flight profiles can still be explained quickly to the nonspecialist, but the branches below it (to the right), where we examine “low-thrust climb” and “gliding approach,” are too technical and detailed for programmatic consideration at a higher level. Thus, one might consider the first level (fuel consumption, cleaner combustion, or seats-per-plane technical approaches) or perhaps a nearby lower level (e.g., more efficient flight profiles versus lower drag on the fuel consumption approach) at this stage in the decision framework.

This kind of decomposition approach, therefore, helps us to develop and consider the basic technical ways to pursue the research theme in question. These, in turn, set broad programmatic directions that can be decomposed by program managers and researchers once the overall direction has been set.

Figure 4.2
Preliminary Breakdown Maps Outlining Key Components for Reduced Emissions



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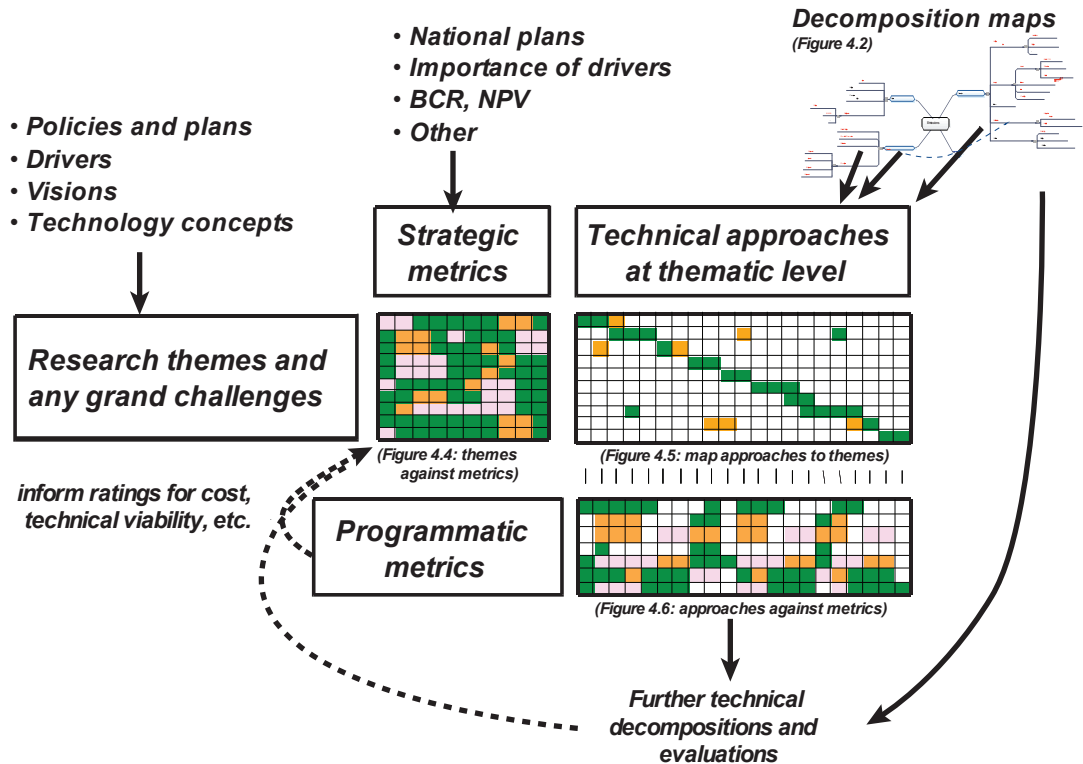
Using this kind of graphical technical map, Appendix B decomposes a number of thematic areas into basic technical approaches for the range of aeronautic principles in U.S. aeronautics policy.

Integrating the Framework Components

Finally, Figure 4.3 illustrates the overall framework hierarchy and process that integrates the three primary stages (grand challenges, research themes, and technical approaches). The matrix illustrations are meant to help in visualizing the application of evaluation metrics against individual options, with the values stored in a color-coded matrix.

1. Grand challenge candidates (if desired), informed by social drivers, imagination, and prior studies, are generated and selected using strategic metrics.
2. Research theme candidates are developed and prioritized using strategic metrics.
3. Technical approaches are generated for each research theme and rated using lower-level programmatic metrics.
4. Technical analysis (at the bottom of the figure) informs the process of generating basic technical approach options for each research theme. It also provides a general understanding of the cost and technical viability of the research themes, illustrating whether there are ideas for meeting these top-level goals. These lower-level technical options can also be evaluated using program-relevant metrics to inform this strategic planning process and in the course of program

Figure 4.3
Hierarchical Decision Framework Components for Prioritizing Research Themes, Grand Challenges, and Technical Approaches



RAND MG997-4.3

definition and management, once research themes and technical approaches have been selected, approved, and funded.

Here, we start in the upper-left corner of Figure 4.3, generating research themes and any grand challenges as discussed above and illustrated in Figure 3.1. These themes and challenges are based on assessments of national policies and plans, data on and decisions about which social and economic drivers are important, visions for where technology might provide solutions and opportunities, and technical concepts arising from the research community. We rate and prioritize these themes and any challenges using strategic metrics based on relevance to national R&D plans, the relative importance of the drivers addressed by the theme or challenge, rough economic assessments of BCR and NPV, and other useful measures selected. (A notional example of measuring these themes is provided in Figure 4.4.)

Moving to the right, we list possible technical approaches to addressing the research themes and any grand challenges. These approaches are developed using information from the relevant decomposition maps (see Figure 4.2). Thus, the second

matrix identifies the mapping between technical approaches and research themes and any grand challenges. The diagonal identifies the primary connections, but complementary or negative effects in other areas are also identified off the diagonal, as illustrated. (Figure 4.5 shows a partial notional example of such a matrix.)

Moving down Figure 4.3, we then assess the technical approaches against programmatic metrics to help prioritize technical approaches to pursuing each research theme and any grand challenge selected for pursuit. (Figure 4.6 illustrates what such a matrix might look like.) This prioritization involves more detail on the viability of pursuing a research theme, as illustrated by the black arrow up to the first matrix on the upper-left side of the figure. Also, further decompositions to more detailed research activities can be informed by the decomposition maps in the upper-right corner and linked to the technical approaches at the thematic level.

Note that one important benefit of separating technical approaches from higher-level research themes is that it simplifies the evaluation of technical approaches. Technical approaches can inherit connections with strategic metrics, such as connections with national policies and plans, without having to continue to justify such connections again. This is more relevant as we move to even lower-level research projects below the basic technical approaches. There, we can focus especially on more research- and project-specific metrics without having to ask whether the research follows national policy or other strategic metrics.

Figure 4.4
Example of How to Prioritize Research Themes and Grand Challenges Using Strategic Metrics

Strategic Metrics	Strategic Metrics																	
	Strategic Metrics																	
	Strategic Metrics																	
	Strategic Metrics																	
	Strategic Metrics																	
	Follows national R&D policy?	Supports national R&D plan	Supports future regulatory requirements	Supports NASA strategic plan	Supports vision 100 (NextGen) R&D plan	Politically viable	Low infrastructure or industry barriers	NASA role	Public appeal	Public good	BCR	NPV	Research risks controlled	Implementation risks controlled	Number of highs	Number of mediums	Number of lows	Unweighted score
Candidate research themes and grand challenges:																		
UAVs in civil airspace	H	H	L	?		M	L	M	M	H	1.5	?	L	L	3	3	4	1
2-3x: NextGen Airspace: increased airspace throughput	H	H	L	?	H	H	L	M	M	H	2.1	?	M	L	6	2	3	2
2-3x: NextGen Airportal: increased airport throughput	H	H	L	?	H	L	L	M	L	H	2.4	?	M	L	4	2	5	2
2-3x: Time-shifting management	H	H	L	?	M	L	H	M	L	H	4.2	?	H	M	5	3	3	2
2-3x: Efficient large aircraft	H	H	L	?	M	H	H	M	H	H	5.1	?	H	H	8	2	1	2
Green aircraft	H	H	H	?		H	M	H	H	H	3.3	?	M	M	7	3	0	2
Revolutionary airplanes: blended-wing body (N+2)	H	H	H	M	?		H	M	H	H	5.1	?	M	M	6	4	0	2
Revolutionary airplanes: future (N+3)	H	H		?		H	L	H			?	?	L	L	6	0	3	2
STOVL/VTOL large transport	H	M	L	?		H	H				?	?	L	L	4	3	3	21
Wide-scale civil airspace rotorcraft	H	M	L	?		H	H			H	0.6	?	L	L	3	2	5	18
Green and safe rotorcraft	H	H	L	?		L	H	H	M	H	0.7	?	L	L	7	0	3	24
General aviation airplane safety	H	H	L	?		L	H	M	M	H	2.4	?	M	L	4	3	3	21
Maintain commercial aviation safety levels	H	H	M	?		H	H	M	H	H	2.2	?	M	L	6	3	1	25
Supersonic flight over land	H	H	M	?		L	L	H	M	M	0.8	?	M	M	3	5	2	21
Air-breathing hypersonic space access	H	H	L	M		H	H	H	H	H	1.1	?	L	L	7	1	3	26
Air-breathing hypersonic missiles	H	H	L	?		H	H	M	M	H	1.2	?	L	L	5	2	3	22
Space re-entry	H	H	L	H		H	H	H	H	H	?	?	L	L	8	0	3	27

Table 4.2
Candidate Strategic Metrics for Prioritizing Grand Challenges and Research Themes

Major Property to Measure	Detailed Metric
Meets goals of national R&D policy and plans	Fraction of goal being addressed (low, medium, or high) or (multiples of 10 percent): mobility, safety, energy, environment, national security, and space exploration
Regulatory requirements	Supports future U.S. regulations Supports future international regulation
Fosters U.S. competitiveness	(May be too abstract to define a metric)
Strategic plan alignment	Supports NASA strategic plan Supports NASA research centers' priorities Supports NASA Vision 100 (NextGen) R&D plan Supports NRC Decadal Survey priority
Other properties	Politically viable Low infrastructure or industrial barriers Government agency or department that is responsible (NASA, FAA, DoD, joint) Public appeal Public good argument Bolsters research capabilities in academia
Well defined	Quantifiable goals? Achievable target year?
Benefits	Overall benefit: social and private (monetary or high, medium, low) Monetary gain to nation (rough estimates in dollars per year) Current dollar losses to nation (rough estimates in dollars per year) Size of annual U.S. market (rough estimates in dollars) Significant social gains (nonmonetary)?
Costs	Research costs: public and private (rough estimates in dollars per year) Subsequent NASA research costs (rough estimates in dollars) Subsequent cost to bring to market and deploy (rough estimates in dollars)
Risks	Science and technology risks Implementation risks Market and economic risk Good risk mitigation plan?
Ratios	NPV or BCR (or expected NPV using risks) Expected value
Score	(Weighted) score

Helps Meet Regulatory Requirements. Knowing whether the option under consideration helps the country meet current or future regulatory requirements will identify the source of the need behind the option.

Fosters U.S. Competitiveness. We did not identify any specific metrics on competitiveness. We believe that the entire process helps to ensure that research investments are targeted at important drivers, and many of those contribute to U.S. competitiveness. However, this does not mean that specific metrics cannot be developed for competitiveness to reflect more specific decisionmaker concerns or available measures. In these cases, the metric developer would need to assess whether the rater of the option on the metric can tie the research and its results to the competitiveness measure in question. Alternatively, a general qualitative metric of competitiveness might be useful, but additional analysis and use of the framework process would be needed to determine if the resulting rating would be a truly useful value or just something that “checks the box.”

Aligns with Strategic Plans. As with national policies and plans, it is useful to know whether the options in question align with other strategic plans and inputs (say, by NASA or in other strategic assessments, such as the NRC’s decadal study (NRC, 2006) or the National Institute of Aerospace’s (NIA’s) aviation plan (NIA, 2005)). Note that these alignments may not be mandatory or equally important. As with national plans, this strategic planning process may inform new versions of NASA’s and other department’s strategic plans. Also, independent study plans are not official documents and do not dictate direction, but it is still useful to know if the candidates align with the analysis from those inputs.

Has Other Useful Properties. Aspects such as public good, public appeal, political viability, agency role (which agency or department in the government has the job to pursue this research—either solely or jointly), and infrastructure barriers provide additional help to the decisionmaker. Again, the importance of each of these properties may vary depending on the option at hand. For example, it is useful to know if the main driver behind a grand challenge or research thrust relates to a public good or not.

Well Defined. This measure asks whether the options, as stated, are framed sufficiently to guide the research path. Quantitative goals and specific targets can help provide objective direction and set a basis to make sure that everyone involved (decisionmakers, managers, and researchers) share the same understanding of the option in question. That is not to say that qualitative challenges and thrusts are not useful, but in some cases, qualitative statements can be subject to too much variance in interpretation.

Benefits. Here, we want to gain some level of understanding of the eventual anticipated benefits from the research. This can be informed by the social and economic factors approach to understanding drivers combined with an assessment of the possible effect that successful research might have on those drivers. As discussed above, monetized estimates should be roughly estimated (e.g., is the potential benefit on the order of \$1 billion per year? \$100 billion per year? \$1 million per year?). Without some

quantification of the potential gains, it is hard to assess the size of the problem we face and how much of an effect the research in question might have. These ratings are probably only rough estimates, but it is likely that some information can be solicited from experts and shared with decisionmakers.

Costs. We also need to understand roughly the costs involved. These costs need to reflect not only the cost of the current research activities but the total costs of completing a research thrust along with subsequent development and market costs. Cost metrics are also important when rating technical approaches and lower-level technical tasks for each approach and within programs. Here, we want to also understand budgetary sufficiency (i.e., are we making only token investments to date on a research area, or are the current budgetary levels sufficient to realize real progress and advance the area in question?). Of course, current budgetary levels may be low because we do not yet have sufficient evidence to show whether a research idea is viable, but there is likely some general understanding in the research community of the size of the overall problem, and the magnitude of those costs need to be shared.

Risks. All research has some level of risk and uncertainty. Researchers and managers will not know all the risks (the so-called “unknown unknowns”) and may have some difficulty articulating them, but they should be able to convey some sense of how much we know about a research challenge, theme, or approach, and of the level of risk. For example, do we need to pursue two or three alternative lines of research to achieve a reasonable level of confidence that we will find at least one solution to the problem? Risk measures will help inform such questions and associated decisionmaking. Especially for early and more fundamental research, the risks are probably higher and less well understood, but researchers still have some sense of the risk, and the metrics should be constructed in a way to elicit and convey what we do know.

Ratios. Here we want to compare the pros and cons of each option along whatever scale is appropriate. How do the benefits compare to the costs? Is there an anticipated NPV, BCR, or other ROI measure, and in what kind of time frame? For example, we probably do not want to spend an estimated \$100 million (including not only the immediate research in question but subsequent research, development, production, associated infrastructure, and other changes) to solve half a problem that has a social value of only \$1 million per year. Conversely, spending \$10 million on something that has a reasonable chance of producing a billion dollars in value would be a much more attractive option to consider.

Score. Finally, it can be useful to generate a (possibly weighted) score across all the metrics in question to help sort out the options (especially if there are a large number of them). Different options are available.

One option is to show a total of the number of low, medium, and high scores that an option received across all metrics.

Another option is to generate a simple scale to quantify the qualitative scale shown. For example, use zero for no value (blank), 1 for low, 2 for medium, and

3 for high. These scalars can be weighted by multiplying each score against a weight for each metric (say, between zero and one). Thus, the total score would be the sum across each metric, m , of the product of the weight for that metric, w_m , times the value of the option, o_m , for the metric:

$$\text{score} = \sum_m w_m o_m.$$

However, it would be important to not put too much emphasis on a simple score for each option because the metrics can be different (“apples and oranges”), the number of metrics of different types may not be equal (or difficult to balance using weights), the relative weightings of the metrics may be too uncertain, and some measures may be more relevant than others when examined case by case in the set of options under consideration. For example, in some cases a decisionmaker may put a lot of weight on a metric of public opinion (e.g., to reflect political views), but in others she or he may decide that other factors are more important (e.g., for a long-term investment reason that has less political support at present).

Evaluating Research Themes and Grand Challenges

The actual selection of the metrics to use in a particular analysis and decisionmaking exercise will depend on stakeholder concerns and priorities. The list above highlights candidates for consideration.

The intent in this step is to provide a simple scoring against these metrics so that the decisionmaker can see a quick, rough approximation of how each candidate scores against the metrics. Alternatively, a weighted score can be produced to give a simple weighted summation across the metric scores. However, it is important to show the individual scores so that decisionmakers can balance pros and cons against various considerations and compensate for the imperfections of any weightings and the relative numbers of different types of metrics. For example, public appeal may be a lesser consideration on some kinds of options than others (say, in cases where research themes address drivers that are more internal to other government functions, such as national defense, and it is harder to show the linkages to the general public).

Figure 4.4 illustrates the application of strategic metrics against a list of candidate research themes from Table 4.1. Here, we used a simple matrix to show the rating of each research theme or grand challenge (in rows labeled on the left) against the strategic metrics (in rows labeled across the top). The values are given in a simple scale of high (H), medium (M), and low (L) with coloring and shading to facilitate a quick overview of how the options perform. The ratings shown are only notional because we did not perform an exercise with domain experts to rate the options. Such an exercise is a reasonable next step for implementing this process with NASA or some other research organization.

Summary scoring is shown on the right, where we total the number of high, medium, and low values for each row. We also provide a simple combined total with a high earning 3 points, a medium earning 2 points, and a low earning 1 point. Presenting individual scores for each rating allows the decisionmaker to see how each theme holds up across the strategic metrics and also to mentally adjust and select themes that are preferred even though they may do poorly against some metrics. That is, a research theme does not necessarily need to score well against all metrics for it to be desirable. For example, some themes may not rise to the level of national visibility in the R&D plan but nevertheless may be valuable for other reasons.

Thus, matrices can then be constructed and completed when applying metrics to the steps in the process: research themes and any grand challenges, basic technical approaches, and even subsequent programmatic breakdowns against more technical programmatic metrics.

Identifying and Mapping Basic Technical Approaches for Addressing Research Themes and Grand Challenges

We now take the decompositions of each theme or challenge from the maps, such as the one in Figure 4.2, to list approaches and map them to the research themes and any grand challenges under consideration. Figure 4.5 provides a notional example of such a mapping. Here, we list part of the candidate research themes and grand challenges on the left side of the matrix. In this case, we list just the green aircraft components of emissions reduction and fuel efficiency improvement along with the next theme of pursuing revolutionary N+2 aircraft types (blended-wing bodies). The technical approaches across the row headers are from parts of the map in Figure 4.2. Here the notional values illustrate that some approaches can contribute to more than one research theme or grand challenge. Thus, this table provides an explicit mapping between approaches and any theme or challenge it may affect.

Note that two kinds of ratings can be desirable when matching technical approaches against metrics:

1. *Alignment*: How strong is the topical relationship between the existing research element and the technical approach (i.e., does this approach directly or indirectly address the goals and objectives of the research theme?). Note that research may support multiple themes, but such multiple high scores may be misleading if used solely to assess the research's worth. This is a common measure of a research activity against a goal: Are we doing anything to help address it?
2. *Significant or Complete*: Perhaps more importantly, we might also ask how much of that research theme or grand challenge would the research achieve if

successful? Here, we want to understand sufficiency. A research program with strong alignment that is nevertheless making very little progress toward any theme is not as valuable as research that, if successful, could go a long way to meeting the theme's objectives. Rating research approaches in this way can help to convey how much real progress we might expect toward the goal. It may inform budgetary sufficiency and convey a sense of whether a research program is really making a difference. A measure such as BCR also reflects this because it considers the benefits anticipated if the research is successful, but considering sufficiency at this level also makes the linkage to the entire research theme or grand challenge.

Evaluating Technical Approaches

We next assess the technical approaches against programmatic metrics. Figure 4.6 illustrates the values of this evaluation in a matrix. In this case, we keep the technical approaches in columns with their labels across the headers. Selected programmatic metrics are listed on the left side in the row labels. Note that in this notional example,

Figure 4.6

Example of How to Prioritize Technical Approaches Using Programmatic Metrics

Technical Approaches: ...		Increase seats per plane Larger planes Different plane geometries Cleaner combustion Reduced fuel consumption More efficient flight profiles Lower drag Less idle time More efficient combustion Shorten distance traveled ...									
Programmatic metrics											
Infrastructure or industry barriers		L	L			M	M	H			
NASA role		M	M			M	M		H	L	
Quantifiable goal		M	M			M	M		H		
Research risks controlled		M	L			M	M	M	L	M	
Implementation risks controlled		L	L			M	M	M	M	L	
BCR		M	H			H	M	M	H	H	
NPV		M	L			H	M	M	M	M	
Number of highs (+1)		0	1			2	1	1	3	1	
Number of mediums (0)		5	2			5	6	4	2	2	
Number of lows (-1)		2	4			0	0	1	1	2	
Unweighted score		-2	-3			2	1	0	2	-1	

we used some strategic metrics from our earlier evaluation of research themes, but we eliminate others. For example, we do not need to evaluate technical approaches to national policy because that has already been done at the research theme level earlier and the value of that mapping is inherited. Other metrics, such as BCR and the anticipated infrastructure or industrial barriers to implementation of proposed concepts, can be valuable at this programmatic level too.

Because in this matrix the metrics are in the rows, we provide scoring at the bottom of the matrix instead of on the right side. Here, we illustrate a different scoring scheme. High ratings are given a score of 1 point. Medium ratings are given a score of 0 points. Low ratings are given a negative score of -1 point. This allows us to interpret the low ratings as a stronger negative. For example, if this prioritization was being done by NASA, then the relevance of the technical approach to NASA's role would be negative if it were low (i.e., not NASA's responsibility).

Conclusions and Recommendations

In grappling with the question of how to determine what aeronautics research the U.S. government should pursue, we came to the following conclusions.

Government's role in funding research is driven by the desire to produce social benefits, especially those for which the private sector does not have sufficient market motivations to produce. This public good consideration can and should be made explicit, even if estimates are only rough. Although research involves significant uncertainties, and there are limitations on our ability to accurately predict how successful the research will be and what its effects will be, there is usually some general sense of the magnitude of the costs and benefits involved, and that sense needs to be conveyed to help inform the decisionmaking, oversight, and justification processes.

Research prioritization and selection should be based on the fundamental drivers of need and opportunity. Those drivers need to be understood and described explicitly to a more specific level than is currently the case. Stakeholder, policy, and political prudence are important to making final decisions, but those decisions will be improved and informed by providing linkages to compelling drivers and opportunities. Absent this, research programs can be subject to criticism for lacking compelling justification, especially in times of budgetary stress.

A structured decision process helps make clear these linkages to need and opportunity. We developed one such process to illustrate how this can be done.

We also exercised the process in the course of creating and refining it, illustrating in the end a reasonable execution of the process (albeit absent the important inputs from decisionmakers and technical experts needed to perform actual strategic planning). Our activity resulted in strategic drivers data (see Appendix A) that drove our development of candidate grand challenges (Chapter Three), research themes (Chapter Four), and technical approaches (Appendix B) that can be considered by NASA and the nation for research.

The net result is an illustrative example set¹ of strategic information and options that could form the basis for government consideration and execution in its strategic

¹ Our example set is not intended to be definitive, yet it is informed by much analysis and serves as a reasonable first iteration that requires further analysis and consideration by government decisionmakers and technical experts.

planning. As we played the role of a tough, shrewd, and practical decisionmaker, our own critique of option reasonableness is reflected in our results. However, it was out of scope for this study to conduct a government strategic planning exercise using our process to develop an actual aeronautics research plan.

Below, we summarize the process we developed and the perspectives and options generated by our illustrative use of the process. We then conclude with some recommendations and observations on future work.

A Prioritization Process Based on Compelling Drivers and Opportunities

When examining what aeronautics research the country should pursue, we recommend using a prioritization process that incorporates

1. multiple perspectives to generate reasonable research options
2. a two-tiered process to group research into research themes that can be assessed at the strategic level and then provide strategic support and direction for lower-level technical approaches and detailed research
3. a set of objective metrics to assess each option
4. a visual presentation to facilitate decisionmaking and explanations.

We review these four components below.

Use Multiple Approaches to Collect Perspectives That Balance the Considerations

First, a multidimensional decision process should be used to generate a reasonable set of research options. By using multiple perspectives, we can leverage the pros of the different approaches for setting research direction while attempting to mitigate their cons through cross-consideration of issues between approaches.

Benefits-driven planning allows one to assess and explain the magnitude of the potential benefits from a line of research and is often the weakest part of current arguments for an increase in aeronautics research investments. Information from the technical analysis helps to mitigate concerns about technical viability and to understand the extent of the potential gains from a line of research investment.

Vision-driven planning using grand challenges can motivate and inspire. As with the needs-driven examination, it needs some level of grounding informed by technical considerations but with the added caution that current limitations do not squelch innovation. Still, we want to make sure that the visions do not violate any laws of physics or are oversold in terms of the anticipated tenure of the research given the difficulty of the problem. So, for example, a problem may be so difficult that it is probably a

very long-term, 50- to 100-year problem, rather than something that could possibly be solved in five years. It is important to make such perspectives known.

Directive-driven planning is important given that decisionmakers have established some reasonable principles already to guide U.S. research (e.g., NSTC, 2006, 2007, 2008, 2010). Although these plans were generated with some perspectives from the other planning approaches, they still did not benefit from in-depth analysis of them. Moreover, the plans were intended to provide a broad sense of the main areas of importance and to help coordinate research across the government rather than dictate decisions to the individual agencies and departments across the government; nor do they come with financial resources to execute the plans.

S&T-driven planning is important to provide both technical grounding and new technical concepts based on innovation. However, sole use of this approach can suffer from evaluator bias (when she or he is involved with the research in question) as well as from disconnects between strategic plans, policies, and social drivers if they are not explicitly considered. It can also suffer from entrenchment of research areas (lacking innovation and new ideas) unless a fresh, open consideration of drivers and vision is examined.

A Two-Stage Process Enables Strategic Examination by Area

Second, simply listing all research ideas in a long list (or even sets of long lists) for examination often leads to excessive work in a flat examination process. For example, we found over 600 research projects within NASA ARMD's recent research portfolio.

We recommend at least a two-stage process. The top level uses broader research themes of sufficient abstraction and reasonable number (about 10 to 25) against which strategic metrics can be applied to facilitate evaluation.

Technical approaches and underlying detailed research projects can then be evaluated at the lower stage using different, more programmatic metrics once the research themes they fit in are approved. This simplifies the evaluation process and also groups the research to provide strategic explanation and justification for lower-level activities that flow from the research themes.

Objective Metrics Reflect Considerations Important to Decisionmakers

Third, the process involves the definition and use of objective metrics to assess the research options across the range of relevant considerations. Table 4.2 lists strategic metrics to consider that cut across a number of policy, drivers, and economic dimensions. The actual metrics used in each process and at each stage are selected to reflect decisionmakers' priorities and what they feel is relevant, and other metrics can be added to this list.

Visualization Techniques Empower Overviews of the Key Information

Finally, it is important at each stage in the process to be able to visualize the range of options, how they rank against all the metrics, and the overall rankings. In this way, the decisionmaker can both see total scorings and also adjust for factors that may not be as relevant to some options as they are to others.

A Illustrative Example of Needs and Research Themes

Here, we summarize our key findings from exercising the process to develop an informed example set of observations across social and economic factors (benefits), potential grand challenges (visions), and intermediate research themes (strategic groupings).

Social and Economic Data Inform the Relative Importance of Aeronautics Research Drivers

Our analysis in Appendix A found significant drivers for continued aeronautics research if viable research opportunities are available; these are summarized below. For each area, we also summarized what we found in our analysis in Appendix B on the basic approaches the country might take to addressing these drivers, informed by the practical issues in our economic and social analysis.

Airspace Throughput Demand Expected to Continue Rising. Historical and forecast data on usage show that demand for airspace system throughput for passengers and cargo will likely increase. Despite unpredictable setbacks, historical trends continue upward, no fundamental changes have appeared to argue for a significant flattening or decrease in demand, and government forecasts also show an anticipated increase.

Regarding approaches: It is not clear whether a doubling or tripling of airspace throughput is best accomplished through an increase in the number of aircraft in the airspace, an increase in the size of the aircraft (keeping the numbers the same), or through time-shifting to spread use across time. Market forces are likely to drive the desired approach, yet, as in the case of improving highway throughput, there may be a government role for creating incentives to influence consumer's choices.

Airline Delays Cost About \$40 Billion Annually. Airline delays have been estimated in the literature at about \$40 billion annually, about half that of one estimate of the cost of motor-vehicle delays.

Regarding approaches: Focus should be on system reliability rather than faster, supersonic vehicles, unless revolutionary concepts emerge (say, to enable green, quiet supersonic flight at transonic prices).

Commercial Air Safety Should Focus on Maintaining Safety for New Systems Rather Than on Improving Safety. Given the relative safety of commercial aviation relative to highway and general aviation, research objectives would be more defensible if they emphasized maintaining safety as we move to new systems (e.g., composite

structures) rather than blindly trying to drive already safe numbers even lower, especially given the higher death rates of other modes of transportation.

Regarding approaches: The current research approaches using nondestructive testing and performance sensors may provide new ways to more rapidly understand composite aircraft failure modes. However, it is also possible that composite structures may have inherently different safety implications that will drive how we treat aging aircraft, giving us the opportunity to weigh the benefits of composite structures against their weaknesses.

General Aviation Safety Is a Bigger Problem (\$3 Billion Annually). Although we have seen some improvement, general aviation safety remains a bigger problem than commercial aviation safety when measured in the number of fatalities per passenger mile, amounting to 100 times more deaths. The main fatality drivers appear to be fire, weather, off-airport landings, and failure to use safety restraints. Because published research indicates that the market effects of commercial crashes appear to be small, market concern is not an overriding motivation to pursue commercial aviation safety over general aviation safety. If the government has a role in all vehicular safety, then it is hard to dismiss this problem, even if the uses are recreational and by a small subset of the population.

Regarding approaches: Even a quick review of the literature has revealed some interesting approaches to dealing with general aviation safety that address the four main drivers, including fire reduction technologies for engines and structures, technologies to reduce pilot error and improve vehicle performance in adverse weather, integrated emergency landing systems, and regulatory and technical approaches to increase the use of safety restraints (as the government already does for automobile safety restraints).

Fuel Costs and CO₂ Reduction Drive Efficiency Demands. Even if the recent spike in fuel costs is short-lived and does not repeat often, broader demands to reduce greenhouse gases will continue to drive efficiency efforts.

Regarding approaches: Technical approaches include improved engines as well as reduced vehicle drag (both through systems research on current tube-and-wing aircraft shapes as well as on new shapes such as blended-wing body and other vehicle arrangements).

CO₂ Reduction Appears More Important Than NO_x Reduction. From total emissions and per passenger mile emissions, CO₂ should be the dominant concern. NO_x emissions are much lower in aviation than in cars, and the total emissions are a very small contribution in total. However, it may be that in local areas, such as airports, NO_x emissions from aircraft is a concern, but we did not have data on whether NO_x levels in those areas are due to aviation or to local automobile emissions.

Regarding approaches: Efforts to reduce fuel consumption (above) have a positive correlative effect on CO₂ reduction. Other efforts may include examination of alternative fuels with lower carbon emissions. However, using hydrogen as a fuel would

require more storage space than for current jet fuel, so it is not clear if hydrogen is a practical alternative. It may be that for some applications, such as air vehicles (or perhaps certain shapes of air vehicles), we will need to continue to use carbon-based fuels while working to offset carbon emissions on ground vehicles or in other ways.

Discussion

For each area under consideration, it is important to weigh aeronautics drivers against broader multimodal drivers and opportunities. As with other investment decisions, alternatives should be considered not only within goal areas but between different domains that affect those areas. Aeronautics is but one mode of transportation, and research investment decisions should consider whether investments are best made within aeronautics or in other modes (or both). For example, trains might be a preferred mode of transportation for short trips because of their superior fuel efficiency and lower carbon emissions. Note that this is in contrast to certain NASA research proposals to pursue an increased use of rotorcraft for short trips to connect passengers to major airports. Rotorcraft have significantly higher safety, fuel efficiency, and carbon emission concerns than, say, trains.

Thus, when examining a driver, we should challenge underlying assumptions to make sure that we are pursuing the best options and can provide explicit explanations and justifications for our decisions to make them as robust and defensible as possible. For example, when considering the airspace capacity problem, we should ask whether the capacity issues are localized or not (e.g., in the Northeast). Can the United States develop a national multimodal transportation plan that examines aviation capacity in the context of other modes of transportation? What are the tradeoffs and investment opportunities in other modes versus aviation (e.g., can we use short-distance, high-speed rail for intercity travel covering less than 500 miles)? What are the cost-benefit differences between modes?

Similar examples can be raised in other areas of consideration. Are the current systems and concepts for surveillance best met with aeronautic vehicles or with such alternatives as satellites or ground-based sensor networks? Assessing each area to understand the drivers relative to alternatives will not only inform decisionmaking but will help others understand what we are doing and why we are doing it, provide budgetary justifications, and even begin to address budgetary sufficiency relative to expected returns.

The examples of the framework described in Chapter Four focus on aeronautic examples, but the conceptual framework can be extended to examine multiple disciplines when looking at candidate research areas, grand challenges, and technical approaches. As with making comparisons between alternative aeronautic approaches, the strategic metrics would help the decisionmaker compare alternatives across multiple disciplines. For example, what are these alternatives and their relative BCRs across such concepts as hybrid rail/air transit in a regional corridor?

Grand Challenges Can Provide Vision Yet Reflect Practical Drivers

Table 5.1 reiterates the set of grand challenges we discussed above. These reflect our combined consideration of possible technical ideas and topics in a general discussion of aeronautics, yet they are tempered by practical aspects that could help keep the vision from producing results that are simply not viable in application. Although not exhaustive, this list offers an informed starting point for future debate and consideration.

Table 5.1
Illustrative Aeronautics Grand Challenges and Themes

Principal Policy Areas	Possible Grand Challenge
Safety	Maintain passenger safety levels as the industry moves from aluminum to composite airplanes
	Make general aviation as safe as commercial passenger air travel
Environment	Planes as fuel efficient as trains
	"Silent" airplane
	Zero greenhouse-gas emission plane (hydrogen plane?)
Airspace	Triple passenger air transport system throughput
	Unmanned vehicles in U.S. civil airspace
Reduced travel time	Green, quiet, supersonic flight at transonic prices
Increased travel comfort	<i>(none—problem not dominated by technology)</i>
Convenience	Safe personal air vehicles
Space access	Practical air-breathing space-access vehicles
National security	Month-long (or even year-long) loitering surveillance aircraft
	Automated unmanned aircraft
	Hypersonic global-strike vehicle
	Unmanned vehicles in U.S. civil airspace
	Cost-effective military vertical envelopment transport vehicles

NOTES: Vertical envelopment is a "tactical maneuver in which troops, either air-dropped or air-landed, attack the rear and flanks of a force, in effect cutting off or encircling the force" (DoD, 2010). See, for example, Grossman et al. (2003) for a discussion of this concept and its technical and logistical challenges.

These Research Themes Can Provide Strategic Focus

The list below reiterates the set of research topics we discussed above. These also reflect our combined consideration of possible technical ideas and topics in general discussion in aeronautics. Unlike grand challenges, these tend to be more like subject areas rather than an end vision tempered by practical aspects. Again, although not exhaustive, this list offers an informed example set for future debate and consideration.

Possible Research Themes to Consider

- UAVs in civil airspace
- 2x-3x: NextGen Air space: increased airspace transport throughput
- 2x-3x: NextGen Air portal: increased airport throughput
- 2x-3x: Time-shifting management
- 2x-3x: Efficient large aircraft
- “Green” aircraft
- Revolutionary airplanes: blended-wing body (N+2)
- Revolutionary airplanes: future (N+3)
- STOVL/VTOL large transport (vertical envelopment/aerial crane)
- Wide-scale civil airspace rotorcraft
- Green and safe rotorcraft
- General aviation airplane safety
- Maintain commercial aviation safety levels
- Supersonic flight over land
- Air-breathing hypersonic space access
- Air-breathing hypersonic missiles
- Space reentry
- Integrate breakthroughs across vehicle in a systems approach.

Some NASA-Specific Considerations

This framework can be applied by any organization involved in selecting and prioritizing aeronautics research options, but the sponsor and primary focus of our analysis was NASA. We suggest that this framework approach can be useful both when creating a new research area for investment as well as when evolving and updating an existing program. In the latter case, the framework can help set new goals and objectives and, over time, can help identify new directions and priorities. Thus, the framework should not require a clean slate; it can be applied to some extent after the fact to help understand how a current program stacks up against strategic and programmatic metrics of the kind discussed.

NASA ARMD should consider employing these approaches in its strategic planning activities as well as in the way it explains its research program. A transparent description of the decision alternatives and processes would help oversight stakeholders and the public understand better the challenges that aeronautics faces and how effective is the government’s budget items for aeronautics relative to the size and importance of the drivers.

ARMD’s current program structure and the major projects within (see the end of Chapter Two) are domain-based rather than theme-based. This sometimes makes

it difficult to exactly understand the challenges that ARMD is facing and the basic approaches it is taking to attack the challenges. That is not to say that this program/project structure is bad, but it means that NASA would benefit from taking steps to make clearer the linkages among its program structure, the strategic challenges it has selected to engage, and the basic approaches it is taking. It is also useful to understand the challenges and approaches NASA has rejected and why. Our planning process and presentation tools would help to make these connections more explicit.

Analysis of Aeronautics Social and Economic Drivers

A wide variety of data offers insights on the significance of the elements that drive aeronautics research. The economic and other quantitative data provide a useful perspective on possible themes for public investment in aeronautics research.

Below, we summarize data that are readily available in the literature. It was beyond the scope of this study to collect new data, but this appendix and the process described in this report give examples of the kind of data that are useful for informing R&D decisionmaking.

We present historic data and forecasts, where available, of indicators in seven areas. These are air travel

- capacity (i.e., demand for air travel)
- delay
- flexibility and comfort
- safety (fatalities)
- fuel costs and efficiency
- emissions (carbon, NO_x, other)
- noise pollution.

We also provide qualitative discussions on selected other areas:

- UAVs in civil air space
- national defense
- space exploration
- fostering U.S. competitiveness.

Aviation security was not addressed in this study, as it is primarily the job not of NASA but of the Transportation Security Administration (TSA) and industry.

Data Sources

Historic data, unless otherwise noted, come from the National Transportation Statistics (NTS) series of the Bureau of Transportation Statistics; this series is available online

and is periodically updated. These statistics originate in a variety of offices within the U.S. Department of Transportation (DOT) and some commercial sources. Forecast data, unless otherwise noted, are from FAA forecasts for fiscal years 2008 to 2025.

Data for commercial air travel include major and regional carriers, commuter carriers, and air taxis, unless otherwise noted. Travel data cover domestic (U.S.) flights only.

Monetizing Social Issues

In some of the analysis below, we were able to provide a simple monetization of social issues to provide a first-order, common basis on which to compare the relative importance of social drivers in different areas.

For example, we can monetize the value of saving travel time, preventing deaths, and reducing carbon emissions through the value of travel time (VOT), value of statistical life (VSL), and social cost of carbon (SCC), respectively. SCC is often expressed as the NPV of the marginal social damage of carbon emissions (see Intergovernmental Panel on Climate Change [IPCC], 2007b, Ch. 20, pp. 821–824). Estimates of the SCC average \$12 per metric ton of CO₂ for 2005. Estimates differ widely across studies because of measurement difficulties.¹

So, if

VOT = \$29 per hour

VSL = \$5 million

SCC = \$12 per metric ton of CO₂,

then we can equate the following:

1 statistical life saved (\$5 million)

≈ 172,000 hours of travel time saved

≈ 417,000 metric tons of CO₂ saved.

This analytic approach is not meant to belittle the value of a human life or any of the other social issues discussed; rather, it is meant to inform overall budget-setting as well as tradeoffs between returns on investment, given limited resources. Higher or lower values can be readily inserted into the calculations to accommodate different valuations.

¹ For example, in a survey of 100 estimates, the values ran from –\$3 per ton of CO₂ up to \$95 per ton of CO₂ (IPCC, 2007b), p. 17.

Demand for Air Travel Capacity

By several measures, domestic air travel demand continues to grow steadily (see Figure 3.1). Although there was a brief dip in demand following the September 11, 2001, terrorist attacks against the United States, the number of scheduled departures, enplaned passengers, and passenger miles are now at their highest levels and are forecast to continue to rise. Between 1975 and 2000, the number of passenger miles nearly quadrupled, the number of enplaned passengers more than tripled, and the number of scheduled departures roughly doubled. Domestic air freight has also increased rapidly in recent years (again, except for a brief period following the September 11, 2001, terrorist attacks). In 2004, the number of aviation freight ton-miles, at more than 16 billion, was about four times the level 20 years earlier (see Figure A.1) The number of enplaned revenue tons,² at nearly 14 million, was still below the levels of the late 1990s but more than triple the levels of the mid-1980s.

Similarly, air freight revenue continues to rise, more so than that of other modes of freight transport, despite the higher cost of air freight over other modes. The latest figures indicate costs more than double that of truck freight and more than 20 times that of rail or water freight (see Figure A.2). At the same time, air freight is but a small fraction of the overall freight market (see Figure A.3). This suggests that air freight is used for small, high-value, or time-critical shipments, where the added price provides value.

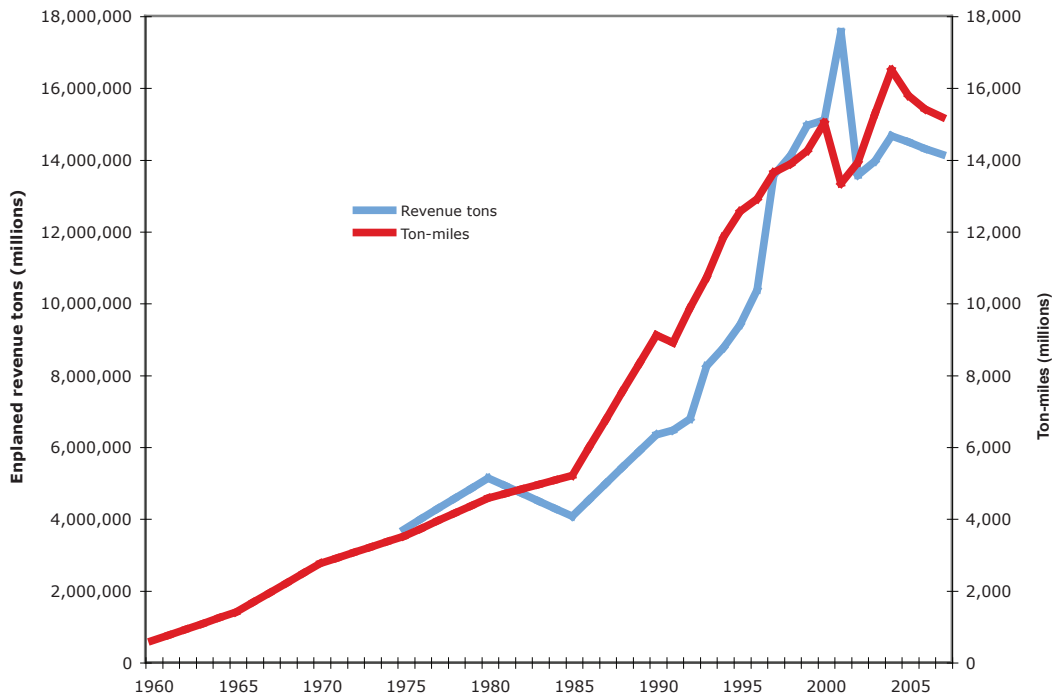
Given the forecasted growth in passenger demand and the historical upward trends in freight demand, the United States will need to increase its air traffic capacity if it is to keep pace. There will probably be brief periods where this growth in demand will dip as a result of unforeseen events (such as economic downturns or safety threats or incidents), but it is reasonable to suggest that the country should plan for, and conduct R&D to provide, increased air traffic capacity to meet this contingency. Development and application of such R&D can be delayed, of course, if major shifts in demand for capacity occur, such as a shift to other modes of transportation, but available trends and forecasts do not yet reflect such shifts.

Air Travel Delay

We now examine available data related to air travel delay and the economic cost of such delays.

² Enplaned revenue tons are the number of short tons transported on a flight by an air carrier (BTS, 2007, Table 1-34).

Figure A.1
Air Freight Enplaned Revenue Tons (1960–2007)



SOURCES: BTS, Table 1-34 (2008b) and Table 1-46a (2009c).

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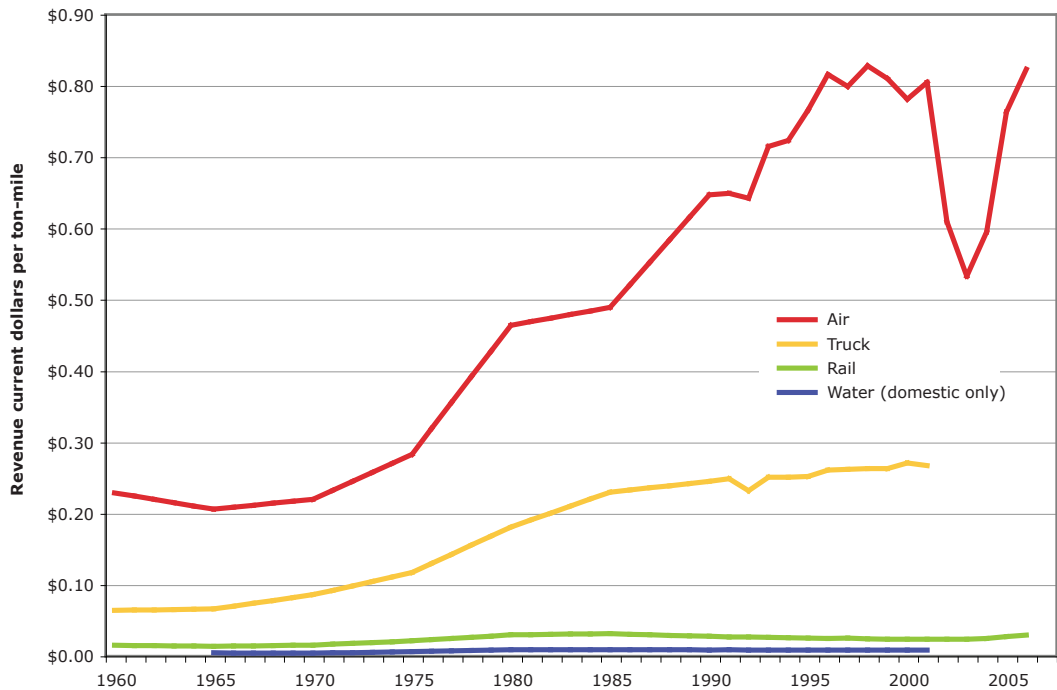
On-Time Arrival Performance Has Slipped Somewhat in Recent Years

Statistics on delays are available in a fair amount of detail (e.g., by individual airports, by airlines, by month, and by the number of minutes delayed). Below, we present two aspects of airline delay: overall arrival delay and the causes of delay.

Figure 3.7 shows on-time arrivals, delayed arrivals, cancellations, and diversions as part of all flights from 1990 to 2008, using information provided to DOT by major air carriers; as of 2008, 19 carriers were reporting. (The percentage they represent of all scheduled flights in the United States is not provided in this data set, but extrapolating from other NTS data on scheduled flights, this appears to constitute about three-quarters of all commercial flights.) Delay over this period has fluctuated between a low of 73 percent in 2000 and a high of 85 percent in 2002. Although on-time performance eroded between 2002 and 2007, it rebounded in 2008 to 76 percent.

Late arrivals are defined as those that reach their destination 15 or more minutes after their schedule arrival time. Canceled flights are defined as those that are canceled less than a week before their scheduled date and time of departure. Canceled flights

Figure A.2
Freight Revenue Ton-Miles Across Transportation Modes (1960–2006)



SOURCE: BTS, Table 3-17 (2008a).

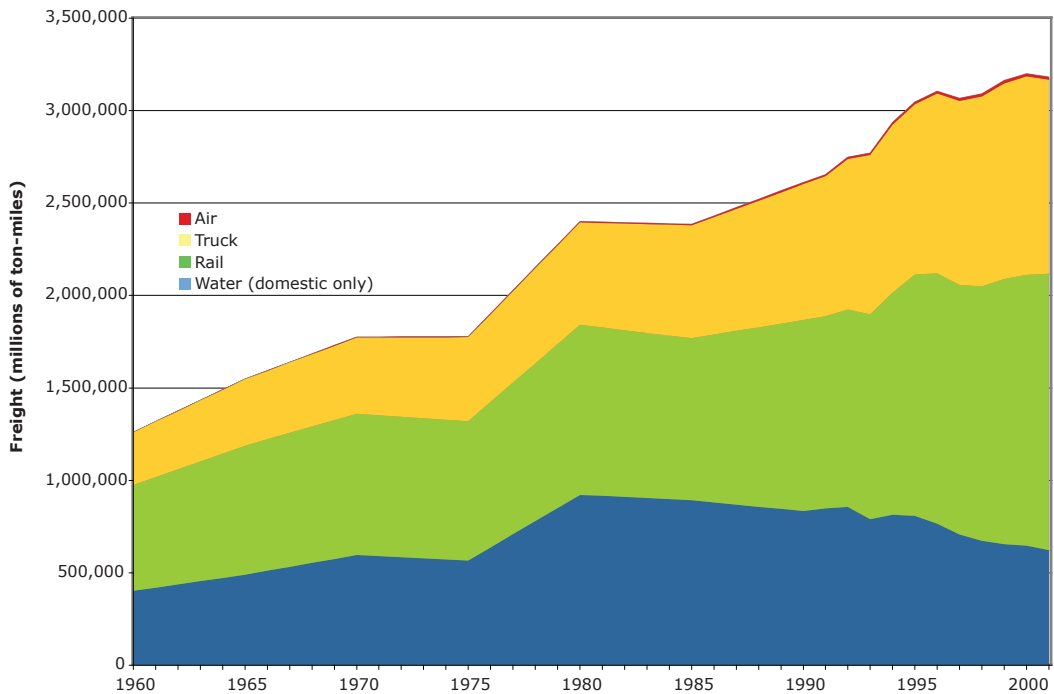
NOTE: Truck and water freight figures are available only through 2001 and air and rail figures through 2006.

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reached a high of 230,000 in 2001, which represented almost 4 percent of flights. Generally, between 1 and 2.5 percent of flights are canceled. Diverted flights—those that arrive at a destination other than the one scheduled—generally constituted less than 0.2 percent of all flights.

Figure A.4 depicts causes of “post-pushback” delays (i.e., delays that occur once the aircraft leaves the gate). For all years, weather was the largest source of delay, sometimes accounting for almost three-quarters of such delays. Other sources of delay fluctuated over time. Airport terminal volume delays declined from over 30 percent in 1990 to just over 10 percent in 2007, and closed runways and taxiways have grown as a source of delay from less than 5 percent in 1990 to more than 10 percent in 2007. The total number of post-pushback delays was at a high of 540,000 in 2007, the last year for which data were available. In previous years, the number ranged from about 250,000 to 500,000. Comparing this to the total number of delayed departures, we find that post-pushback delays generally constitute between 30 and 40 percent of all departure delays. The majority of delays, therefore, occur before the aircraft leaves the gate. Statistics on the cause of these delays were not readily available.

Figure A.3
Freight Volume Across Modes (1960–2001)



SOURCE: BTS, Table 1-46 (2009c).

NOTES: Data were originally downloaded by BTS in 2007. Since then, truck figures have been revised post-1990, meaning that they are not comparable with pre-1990 figures. These earlier figures have not been revised.

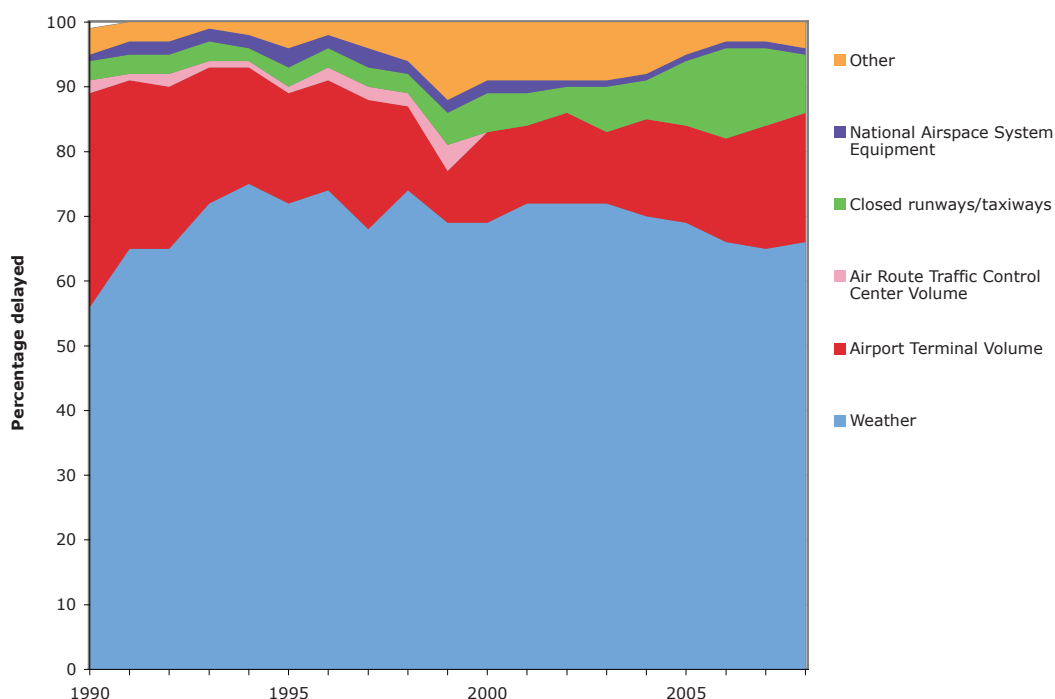
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Airline Delays May Cost Billions Annually—Possibly One-Fifth That of Motor-Vehicle Delays

Delay costs to both the airlines and the economy as a whole have been estimated by various sources. The ATA, which represents major commercial airlines as well as other aviation businesses, estimates that each minute of aircraft delay time costs about \$61, for a total of \$6.1 billion dollars for the calendar year 2008 (ATA, 2010b).

In a 2008 speech, then-Transportation Secretary Mary Peters estimated that airline delays cost \$15 billion (Wilber, 2008). However, no study or other data were cited to support this figure, and it is not clear if this includes direct costs to the airlines. In contrast, delay in motor-vehicle travel is estimated by the Texas Transportation Institute to cost \$78 billion annually in lost time (4.2 billion hours) and in wasted fuel (2.9 billion gallons) (Schrack and Lomax, 2007).

Figure A.4
Sources and Percentages of “Post-Pushback” Delays of Major Air Carriers (1990–2008)



SOURCE: BTS, Table 1-61 (2009c).

NOTES: Information on air route traffic control center volume as a cause has been unavailable since 2000 but as of 2008 is included as part of the category “airport terminal volume.”

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These estimates may include biases and rough estimates, but they indicate that the economic cost of delays may be in the billions of dollars.

Valuing Travel Time Savings

The value of travel time is an economic estimate of the average willingness of people to pay for travel time savings. VOT is typically estimated from data on people’s choices between travel options that differ in travel time and monetary costs.

Table A.1 shows the estimated VOTs for personal and business travel from a study performed by GRA, Inc., for the FAA in 2004, based on guidance from the Office of the Secretary of Transportation (OST, 2003).³ Here, the VOT reflects the opportunity cost equal to the individual’s value of time in forgone work or leisure activity, plus any discomfort cost (GRA, 2007).

It is interesting to note that the value on an hour ranges from only \$23 to \$40. Thus, for aeronautics concepts such as supersonic flight, the incremental cost to fly

³ See also Bruzelius (1979), OST (2003), and FAA (2003).

Table A.1
Hourly Value of Travel

Trip Purpose	Value of Travel Time (\$2,000 per person)	Sensitivity Range	
		Low	High
Air carrier			
Personal travel	\$23.30	\$20.00	\$30.00
Business travel	\$40.10	\$32.10	\$48.10
Average across trip purposes	\$28.60	\$23.80	\$35.60
General aviation			
Personal travel	\$31.50	NR	NR
Business travel	\$45.00	NR	NR
Average across trip purposes	\$37.20	NR	NR

SOURCE: GRA Inc. (2007).
NOTE: NR = not reported.

supersonically rather than transonically below the sound barrier would need to be minimal to maintain a commercially viable business (unless, of course, a discontinuity in VOT occurs in certain cases). For example, reducing a cross-country flight from five hours to three hours by flying supersonically would result in a VOT of only about \$80, so supersonic flight for the general population would have to be very close to subsonic flight prices if these VOT values hold. However, it might be that for very long flights or very significant reductions (e.g., transcontinental flights lasting 15–30 hours), the VOT might be higher for a significant portion of the population if travel time could be cut in half, say. Nevertheless, if these VOT values are reasonable, then significant savings in flight time may not be worth much to the general population on a per flight basis.

Discussion

These VOT data show that it might be prudent for the United States to focus on meeting capacity demands (e.g., via NGATS) rather than pursuing faster flying vehicles. However, it might be interesting to consider a grand challenge that reflects these findings, for example, pursuing increased speed at the same cost—say, green, quiet, supersonic flight at transonic prices.

As with air system capacity, the United States should probably also look for balances across transportation modes if delays are to be reduced. For example, is it better to reduce the delays and unpredictability of the time needed to drive to the airport than simply pursuing faster flight? This question could be addressed using the framework described in the main body of this report by including these options explicitly.

The decisionmaker can then see how the aeronautics options compare to the options that reduce driving time in terms of cost, infrastructure difficulty, time saved, emissions, fuel savings, etc.

Aviation Safety

We now examine the social drivers of research on aviation safety, focusing on fatalities.

Commercial Aviation Is Already Safer Than Driving per Passenger Mile

We examined the drivers of research on aviation safety and compared the safety of air travel to automobile travel in two ways: per passenger mile and per trip. Figure 3.3 graphs the safety trends over time of commercial aviation, general aviation, and highway travel (defined as all driving) on the basis of the number of fatalities per billion passenger miles traveled. Commercial air travel (defined as a combination of air carriers, commuter carriers, and air taxis) is the safest of the three modes, with generally less than one fatality per billion miles flown per year. Highway travel (a mode that often competes with commercial air travel) is in the range of nine or ten fatalities per billion passenger miles. Rates for both modes have been relatively stable since the 1990s. The number of commercial air fatalities tends to fluctuate more from year to year, with 2001 a large exception to the generally low total. However, even with a major airline crash, the fatalities number in the tens or hundreds. In contrast, highway travel kills about 43,000 persons per year—a number that has remained steady since 1990 even though the number of miles driven has increased.

General Aviation Fatality Rates Are Over Ten Times Higher Than Commercial Aviation Rates

In contrast, data on general aviation safety show fatality rates far higher than those of commercial aviation or driving. As Figure 3.4 shows, general aviation fatality rates have dropped substantially since 1990, but there are still about 35 fatalities per billion passenger miles traveled.

In absolute terms of fatalities, there are over 100 times more fatalities in general aviation than in commercial aviation: On average, 560 people are killed in general aviation crashes each year but only about 18 are killed annually in commercial aviation (see Table A.2). Data from the U.S. Civil Helicopter Safety Statistics Summary Report, from 1997 to 2006, show that between 7 and 12 percent of fatalities are related to helicopter crashes.

The number of highway fatalities per year is almost 100 times higher than that for general aviation (and 10,000 times higher than for commercial aviation), with about 43,000 deaths per year on highways.

Table A.2
Average Number of Accidents Annually (2004–2008)

	Commercial Air Carriers	Commuter Air Carriers	On-Demand Air Taxis	General Aviation
Total accidents	32	4.6	61	1,600
Total accidents involving fatalities	2	0.2	15	300
Fatalities	18	0.4	41	560
Seriously injured persons	13	0.6	16	260

SOURCES: BTS (2008d), Table 2-9; (2009c), Tables 2-10, 2-13, and 2-14; and NTSB (2009), Tables 3 and 5.
NOTE: Data are rounded to two significant digits.

It Is Less Clear Whether Air Travel Is Safer Than Automobile Travel per Trip, but Car Trips Are Much Shorter

The number of highway fatalities has been in the range of nine to ten per 100 million passenger trips since 1990, whereas airline rates vary greatly from year to year—some years zero, some years over 30 (see Figure A.5). (These data include only air carriers, not commuter flights or air taxis, since trip numbers were not available for those modes of travel.) In the period 1990 to 2006, the number of airline fatalities per trip was higher than the number of highway fatalities in six years. When averaged over the period from 1990 to 2006, the number of airline trip fatalities was about double the number of highway trip fatalities: 19 versus 9.5.

Of course, most commercial aviation trips are much longer than automobile trips (which are generally very short), so this comparison has a mixed message. Nevertheless, from a safety perspective, it is enlightening to consider the sources of travel risk as we pursue the best modes of transportation and consider where to invest our research dollars. Data on number of fatalities per trip for general aviation are not available, so we cannot determine the number of fatalities per 100 million passenger trips.

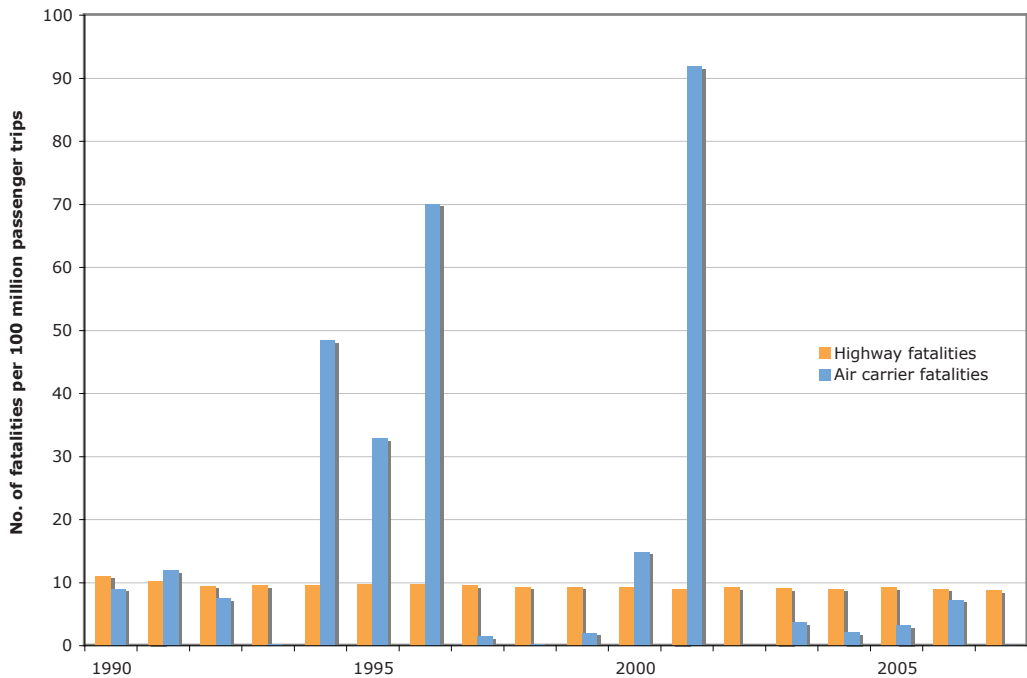
It is beyond the scope of this study to assess risk per trip versus risk per mile, but one might hypothesize that automobile risk rates may be relatively constant per mile, whereas airplane risks may be more constant on a trip basis if risk is concentrated on takeoffs and landings. Automobile risks may also differ depending on the road traveled (e.g., residential streets versus highways).

The Economic Cost of General Aviation Deaths Is About \$3 Billion Annually

The value of statistical life is societal willingness to pay for an intervention that reduces the risk of death divided by the reduction in risk that the intervention entails. VSL estimates range between \$4 million and \$9 million per person (Viscusi and Aldy, 2003).

Table A.3 shows the monetized annual cost of fatalities from air and automobile travel, assuming a \$5 million VSL. On the aviation side, general aviation costs from fatalities are by far the largest, at about \$3 billion annually. In comparison, the annual

Figure A.5
Number of Fatalities per Passenger Trip (1990–2007)



SOURCE: Authors’ calculations based on BTS, Tables 1-37 and 2-1 (2010a).

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Table A.3
Monetized Annual Cost of Lost Life, by Transportation Sector

	Average Number of Fatalities Annually (2004–2008)	Annual Cost of Lost Life (\$ billions)
Air carriers	18	\$0.09
Commuter carriers	0.4	\$0.002
On-demand air taxis	41.4	\$0.21
General aviation	563.6	\$2.8
Total	623.4	\$3.1
Highway (automobile)	41,475	\$207

SOURCES: U.S. air travel: BTS (2008d), Table 2-9; (2009c), Tables 2-10, 2-13, and 2-14; and NTSB (2009), Tables 3 and 5. Highway: BTS (2009b), Table 2-17, and NHTSA (2009).

NOTES: The table includes only domestic fatalities and assumes a value of \$5 million per lost life. Data are rounded to two significant digits. Totals may not equal the sum of components because of independent rounding.

cost from commercial air carrier fatalities is only about \$90 million and from on-demand air taxis, only about \$200 million.

As expected from our discussion of relative fatality rates, highway fatality social costs are about 100 times higher than general aviation's, at just over \$200 billion annually.

The Market Effects of Commercial Crashes on Private Carriers Appears to Be Small

Another economic aspect of aviation safety is the market effects of commercial crashes on air carriers. Changes in stock price (i.e., equity value) indicate investor expectation of changes in future earnings. Bornstein and Zimmerman (1988) found that a fatal crash results in a very modest 1 percent reduction in an airline's equity value, which equates, on average, to a \$4.5 million loss in 1985 dollars. Chalk (1986, 1987) and Bosch, Eckard, and Singal (1998) found slightly larger impacts (1.2–3.5 percent).

Analysts have also tried to analyze the effect of a fatal crash on other carriers' stock price to determine the broader market effects of crashes. Bosch, Eckard, and Singal (1998) found that "Noncrash airlines with little market overlap lose value whereas close rivals, on average, experience slight gains." Overall, the effect of a crash on noncrash carriers is small and not statistically significant in that study.

Finally, Bornstein and Zimmerman (1988) note that "the average loss in equity value . . . is much smaller than the total social costs of an accident, reflecting the fact that airlines are insured against many of the costs of a crash."

Thus, existing reports in the literature indicate that the social costs discussed above are much more significant and therefore should be a more useful determinant for informing investment decisionmaking on aviation safety.

Discussion

The number of general aviation fatalities annually is more than 100 times higher than fatalities in commercial passenger transport. Fatality rates per passenger mile are also about 30 times higher for general aviation than for commercial aviation. These data indicate that it would make sense to focus any commercial aviation safety R&D on maintaining current safety rates rather than on reducing them. As the United States moves to new materials (composites instead of aluminum) and higher-density air traffic control (in a world that experiences two to three times more flights than at present), a focus on maintaining safety levels makes sense given the uncertainties associated with these trends (i.e., we do not know whether these changes will result in higher safety risks).

Commercial aviation is also much safer than highway automobile travel. The number of deaths per passenger mile is at least ten times lower, and the total number of deaths annually is over 2,000 times lower.

Such analysis should be used to inform NASA and broader U.S. government safety objectives and priorities. Thus, emphasis on reducing (rather than maintaining)

accident rates for commercial aviation in the 2007 national R&D plan (NSTC, 2007) may be misguided, given other, more significant safety issues, such as general aviation safety. Maintaining safety may still require investments, given changes in vehicle structures, technology, air traffic controls, and other factors, but the question is, which goals should the country establish to help guide the extent and focus of safety research? Explicit targets can be used as metrics in the decision framework outlined in Chapter Four. Moreover, the cost-benefit tradeoffs (NPV) of the research options can explicitly show how big an effort a particular candidate safety research option offers. Also, comparative safety research investments in other, non-aeronautics disciplines can be shown for comparison purposes, to help decisionmakers understand the relative value of research across domains.

The \$3 billion annual general aviation fatality problem is significant enough to warrant attention, and R&D ideas (investment opportunities) for general aviation safety are called for. A general aviation safety grand challenge might be warranted as a way to motivate creative thinking on how to improve general aviation safety. General aviation safety is not a trivial topic, but its vehicles cost generally much less than commercial transport vehicles and have lower performance reserves. The general aviation industry also has much less RDT&E resources. NASA has some activities related to general aviation safety, especially for rotorcraft. Appendix B describes some possible general aviation safety technology ideas that could be pursued.

In conclusion, the safety data discussed above indicate that the United States should strive to maintain current civil aviation safety levels but should not spend excess effort trying to improve what is already exceptionally safe. New efforts should be considered to increase general aviation safety; current attention to improving rotorcraft safety is a start.

Fuel Costs and Consumption

We now examine costs and drivers of research related to fuel consumption.

The Recent Surge More Than Doubled Jet Fuel Prices, Outpacing Efficiency

Figure 3.6 shows three indicators of fuel cost and consumption, all adjusted such that the 1990 values equal 100, to demonstrate the difference in the trends. The number of miles flown per gallon has increased steadily since 1990, from 0.29 miles per gallon in 1990 to 0.43 in 2007, the last year for which data are available (neither the FAA nor the EIA forecasts total miles flown, which is the measure used as the basis for these figures).⁴ Total fuel consumption is projected to rise by about 40 percent—from 16

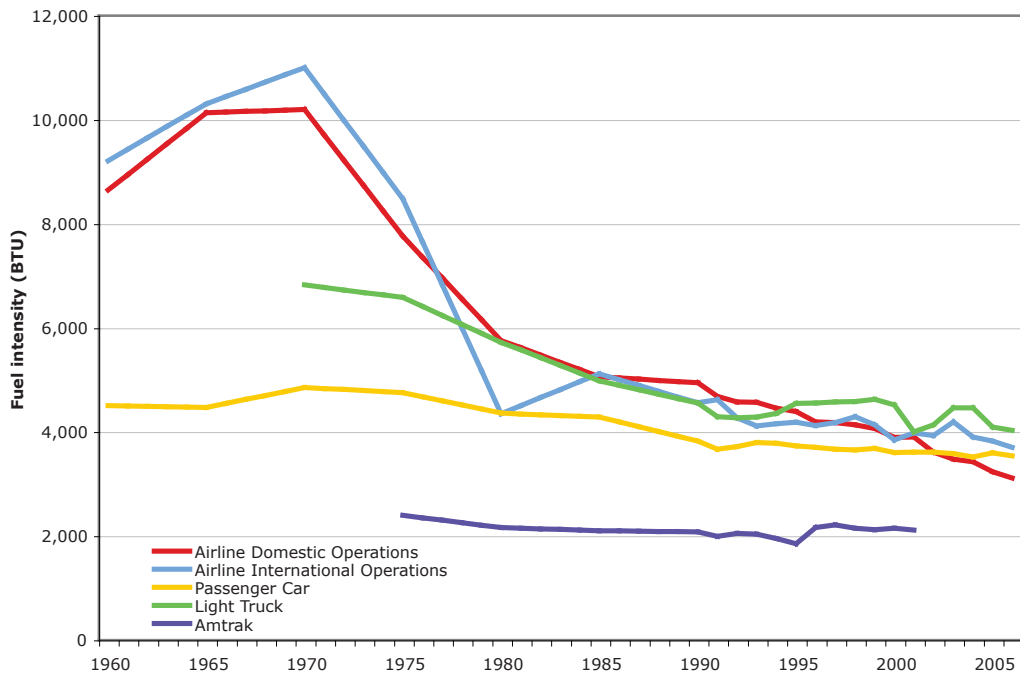
⁴ It is interesting to note that miles per gallon averaged 0.41 in 1960. We did not investigate the factors behind the decline in fuel efficiency between 1960 and 1990, but there is some additional technical discussion in Appendix B on fuel efficiency per passenger mile (see Figures B.3 and B.4 and the associated discussion).

billion gallons in 1990 to 23 billion gallons in 2025. Jet fuel prices (in current dollars) have fluctuated widely, doubling from 90 cents per gallon in 2000 to almost \$2 in 2007 (the last year for which historic data are available). FAA forecasts assume that they will remain at historically high levels for the next 20 years, although fuel prices are affected by a number of factors and can increase or decrease dramatically in a short period of time.

Airline Fuel Efficiency per Passenger Mile Has Approached That of Cars, But Is Twice That of Trains

Figure A.6 graphs the fuel consumption (intensity) of various transportation modes in British thermal units (BTU) per passenger mile. Data were available for both domestic and international air travel (for U.S. carriers only) and are graphed separately. As the figure shows, through about 1980, air travel was considerably more fuel intensive than highway travel (for both cars and light trucks), but around 1980, the trends began converging. All four modes have remained around 3,500 to 5,000 BTU per passenger

Figure A.6
Aviation Fuel Consumption Efficiency per Passenger Mile Relative to Cars, Trucks, and Trains (1990–2006)



SOURCE: BTS, Table 4-20 (2008c).

NOTE: BTS data are available only through 2006.

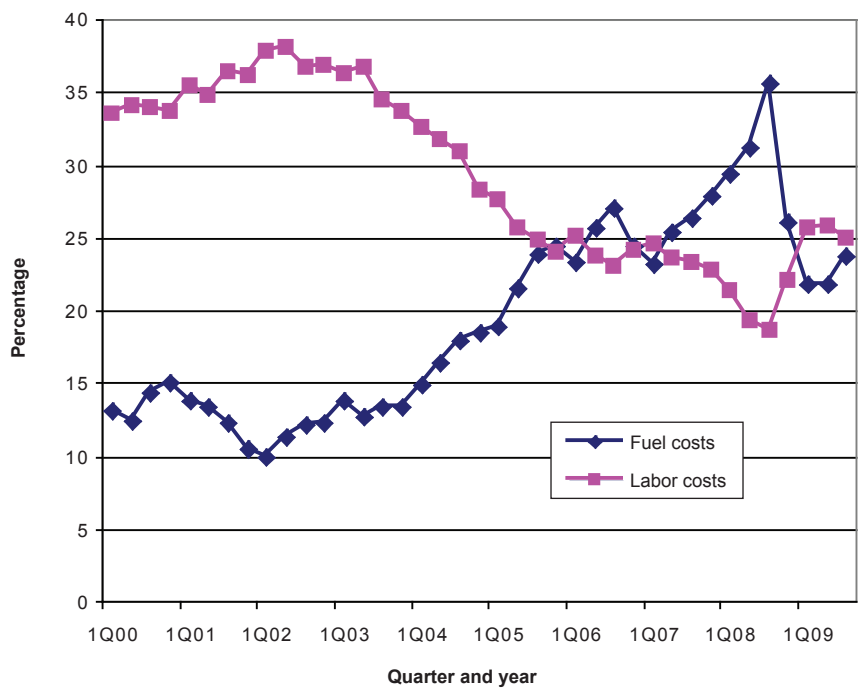
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mile for the past several decades. However, all of these modes are still approximately double the fuel intensity of passenger rail (Amtrak, in the United States), which has been consistently around 2,000 BTU per passenger mile for the period for which data are available (1975 to 2000). Forecasts of fuel intensity were not available.

Fuel Costs Are About a Quarter of Ticket Costs and as Big as Labor Costs

Figure A.7 shows the portion of airline operating costs related to fuel prices from the first quarter of 2000 to the third quarter of 2009. As a percentage of airline operating expenses, fuel costs have risen from about 12 percent to over 20 percent, with a spike to 35.6 percent in the third quarter of 2008. Thus, during the recent surge, when fuel prices rose 3.5 times higher than in 1990 (and about five times higher than the low price in 1998), fuel became as large as or larger a contributor than labor to airline costs.

Figure A.7
Fuel and Labor Costs as a Portion of Passenger Airline Costs (2000–2009)



SOURCE: ATA (2010) based on DOT Form 41.
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Discussion

During the recent fuel price surge and beyond, fuel efficiency has become a significant concern for the aviation industry. However, it is unclear whether the fuel price forecast will remain at such historically high levels or whether recent experience represents a price bubble that will burst, leaving us with more traditional lower prices. Nevertheless, these data can be useful when prioritizing research agendas and comparing them to other areas of investment.

Aviation Emissions

We now examine available data on emissions from aircraft.

Carbon Emissions Appear to Be the Dominant Concern

The main aviation pollutant (based on emission volume) is CO₂, a major greenhouse gas.⁵ Air travel produced about 3 percent of all carbon emissions in the United States in 2007 (see Figure 3.5).⁶ The entire transportation sector accounts for about one-third of carbon emissions (see Figure A.8), of which the majority is from gasoline (i.e., primarily for ground vehicles). Commercial air travel accounts for about 9 percent of total transportation emissions.⁷ Figures from the EIA for the period through 2030 predict that this proportion will grow modestly to almost 4 percent, whereas the contribution of gasoline will decrease from 20 to 16 percent (EIA, 2009a, Table 19).

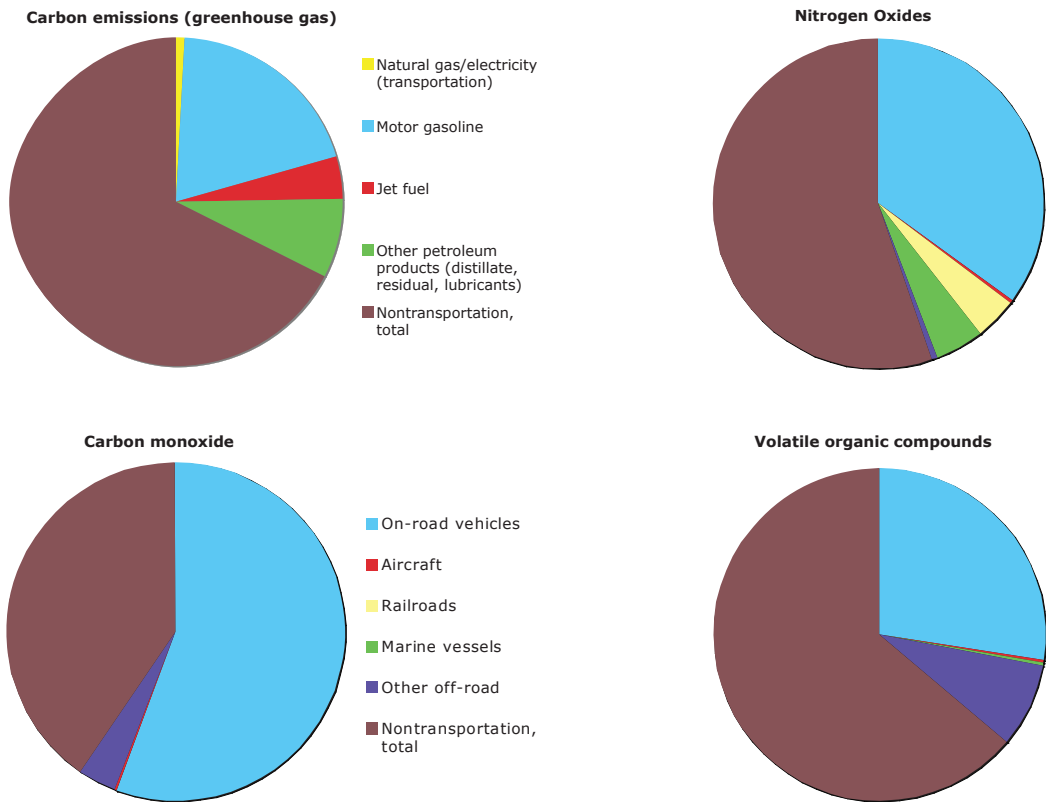
On a passenger mile basis, air travel currently produces about 25 percent more carbon emissions than driving does (see Figure 3.5). Air travel carbon emissions have been declining on a passenger mile basis since 1990, when they were over 130 tons per million passenger miles. By 2007, aviation produced about 80 tons of carbon per million passenger miles, whereas driving created about 65 tons per million passenger miles. According to projections from EIA (2009a), emissions from both will continue to fall but with aviation still remaining higher than driving by about 20 percent (down from 25 percent).

⁵ CO₂ is the principal greenhouse gas resulting from or produced by humans that affects the earth's radiative balance (IPCC, 2007a). The other primary greenhouse gases in the earth's atmosphere are water vapor (H₂O), carbon monoxide (CO), methane (CH₄), nitrous oxide (N₂O)—one of the nitrogen oxides, and ozone (O₃).

⁶ NTS provided estimates in millions of metric tons of carbon (see BTS, 2009a, Table 4-49). Where other sources provided figures in millions of metric tons of CO₂, we converted them to carbon figures using a ratio of 12.01 (the mass of one mole of carbon) to 44.01 (the mass of one mole of CO₂).

⁷ Although NTS does not break down emissions from jet fuel into civilian and military categories, EIA estimates do. We extrapolated from their figures that approximately 79 percent of all jet fuel is used by commercial aviation.

Figure A.8
CO₂, NO_x, CO, and VOC Emissions, by Transportation Sector (2002)



SOURCES: BTS, Tables 4-40, 4-41, 4-42, and 4-49 (2007).

NOTE: These data were initially downloaded in 2007. Since that time, reporting methods for carbon monoxide, nitrogen oxides, and volatile organic compounds have changed and aircraft are no longer reported as a separate category. Therefore we have not attempted to update these data.

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The Social Cost of Aviation CO₂ Emissions Is About \$3 Billion Annually—One-Fifth That of Automobiles

By using the average SCC of \$12 per metric ton of CO₂ for 2005 (as described above), we can explicitly evaluate CO₂ reductions.

Table A.4 estimates the current social cost of aviation CO₂ emissions at almost \$3 billion annually. In comparison, the social cost of automobile CO₂ emissions is about five times that of aviation emissions—about \$14 billion.

Table A.4
Estimated Social Costs of CO₂ Emissions from Aviation and Automobiles

	Annual Emissions (million metric tons CO ₂ , 2008)	Annual Social Cost of CO ₂ Emissions (\$ billions)
Jet fuel	226.3	\$2.7
Aviation gasoline	2.0	\$0.024
Total aviation	228.3	\$2.7
Automobile gasoline	1,134.9	\$14

SOURCE: EIA (2009b), Table 10.

NOTES: The average SCC figure of \$12 per ton of CO₂ emissions is used in the table. Totals for carbon in the right column do not equal the sum of components because of independent rounding to two significant digits.

Aircraft NO_x Emissions per Passenger Mile Are One-Tenth That of Automobiles

For other pollutants (i.e., volatile organic compounds, carbon monoxide, and NO_x), the total produced by air travel is less than 1 percent of total emissions from human activity.⁸

The amount emitted per passenger mile is also relatively small. For example, NO_x emissions from air travel are about 0.2 ton per million passenger miles, whereas auto travel emits over 1.5 tons per million passenger miles—almost ten times higher. Thus, per passenger mile, air travel already has much lower NO_x emissions than automobile travel.

Some technical arguments claim that high-atmosphere emissions have bigger global warming effects per ton, but the reliability of these assertions has not been clearly established nor has the extent of these bigger impacts. It certainly would be useful to know if these effects would be disproportionately larger, but absent strong scientific consensus, the effect of NO_x emissions relative to other greenhouse gas emissions should not be magnified.

As a result, CO₂ emissions appear to be the major concern for air travel and should therefore be the dominant concern when setting research objectives for aeronautics chemical emissions.

⁸ When we first retrieved data from the NTS in late 2007, estimates for aircraft emissions of criteria pollutants were available. When updating these figures in 2009, the data no longer provided a category for aircraft, only nonhighway transportation use.

Discussion

As mentioned above, CO₂ appears to be the largest concern for aeronautics emissions research, and an annual \$3 billion problem could warrant significant budgetary attention. Reducing CO₂ emissions significantly could be a useful grand challenge (say, to bring such emissions to the same level per passenger mile as for automobiles), but this does not necessarily mean that aeronautics research is the best overall CO₂ R&D investment. Aviation CO₂ emissions are relatively low (only 4 percent of total emissions and only 12 percent of all transportation emissions).

It would be useful to assess the feasibility of either CO₂ reduction through fuel efficiencies (CO₂ reduction and fuel efficiency efforts are positively correlated) or of using alternative fuels that have a lower CO₂ emissions rate. For example, is there an energy density or fundamental engine problem that would make hydrogen air vehicles inefficient? Should aeronautics research be the first (or best) CO₂ research target for the government? A possible next step (or at least part of any research proposal) might be to calculate potential gains against tradeoff candidates to assess whether potentially higher payoffs (returns on investment) may be possible in other areas of carbon reduction.

Finally, the summary numbers above indicate that less emphasis should be placed on NO_x reduction than on CO₂ reduction. Aviation NO_x emissions in total are a very small part of overall emissions in the transportation sector, and on a per passenger mile basis, they are much lower than in automobile travel. Thus, emphasis on NO_x emissions might be better focused on maintaining current levels as new engine and alternative fuel technologies are introduced rather than on reducing NO_x emissions. For example, the research community might find technical approaches where significant reductions in CO₂ emissions could be achieved at the expense of keeping NO_x emissions level, but such tradeoffs would need to be informed by high-level priorities rather than blanket priorities that give CO₂ and NO_x the same level of importance.

Noise Emissions

In many respects, trends in noise are more difficult to quantify and analyze than other trends, for several reasons. First, noise is inherently local, in that it disproportionately affects persons living fairly close to airports. Second, although noise can be measured objectively, the experience of noise is subjective; noise that does not bother some people can be very bothersome to others. Nevertheless, some data and perspectives are possible and are important to consider when prioritizing investment opportunities.

\$420 Million Has Been Spent Annually on Airport Noise Abatement, Affecting 500,000 People

Airport stakeholders generally analyze noise around airports and develop contour maps that show which areas are exposed to what noise levels down to 65 decibels (dB). The usual standard is the “day-night average A-weighted sound level” (DNL).⁹ Airports can apply for federal money to mitigate noise effects at 65 dB and above if they participate in the FAA’s Part-150 Noise Compatibility Program. This voluntary program allows airports to request noise set-aside funding from the Airport Improvement Program. Mitigation generally includes soundproofing buildings or buying land near airports to protect it from future development. However, there are other funding programs for noise mitigation, and some of the country’s largest airports do not participate in Part-150. A total of \$6.6 billion was spent in FY 1992–FY 2007 on noise abatement programs for airports, for an average of \$413 million annually (see FAA, 2007—the most recent report available).

According to the FAA, the number of people living within the 65 dB noise contours of airports has been reduced by 95 percent in the last 35 years (Waitz et al., 2004). As of 2000, 500,000 people in the United States lived in areas experiencing 65 dB or above; an additional 5 million live in areas experiencing over 55 dB. This reduction occurred even though air traffic continued to grow during this period; the changes were due largely to new certification standards as well as to the phasing out of 55 percent of the older aircraft fleet as a result of the Airport Noise and Capacity Act of 1990 (Title IX, Subtitle D of the Omnibus Budget Reconciliation Act of 1990, Public Law 101-508). This act required that the FAA establish a program to review noise and to phase out Stage 2 aircraft.¹⁰

The same report also notes that aircraft noise causes the greatest local objection to airport expansion. For this reason, a National Academies of Science report (2002) recommended shifting some of the federal money for mitigating noise effects to research on lessening noise. A GAO report noted that noise was one of several reasons that runways take approximately ten years to build—from the planning and environmental phases through design and construction (GAO, 2003).

Regulatory Pressures

In addition to noise abatement laws and regulations, the United States and the EU have current and evolving regulatory pressures that could also motivate R&D on aircraft noise reduction. An assessment of where U.S. and EU future regulatory restrictions appear headed based on targeted social benefits could help reveal the magnitude

⁹ The Occupational Safety and Health Administration identifies an exposure of 90 dB for more than eight hours as the maximum permissible at a worksite (see Code of Federal Regulations, Title 29, Part 1910.95(b)(2)).

¹⁰ A Stage 2 aircraft is an aircraft that has been shown to comply with Stage 2 noise levels and that does not comply with the requirements for a Stage 3 airplane (see Code of Federal Regulations, Title 14, Section 36.1(f)).

of the problem, especially if we consider the current state of the art on noise abatement and locate the gaps. Resulting research could be tied to the broader aeronautics objectives of advancing U.S. competitiveness, especially given EU regulatory trends that would affect how U.S. companies can play in European markets.

Explore New Vehicle Types

We now discuss briefly some qualitative drivers of research into new aeronautics vehicle types.

Unmanned Aerial Vehicles

Perhaps the most striking change in vehicle demands is that for unmanned aerial vehicles. The use of remotely piloted (usually via satellite communications) and global positioning system (GPS)-guided vehicles has exploded and garnered much attention as vehicles for military intelligence, surveillance, and reconnaissance (ISR) and weapons delivery. Also, commercial uses of UAVs are increasingly being discussed.

UAVs in Civil Air Space

Both military and commercial uses are driving demands for operating such vehicles in commercial air space. (This is in contrast to the previously dominant unmanned vehicles—cruise missiles.) This need is already driving aeronautics research and will continue to do so to resolve safety and control issues.

New UAV Concepts and Capabilities

Another research question surrounds research on UAVs themselves. Current-generation UAVs tend to use existing engines rather than developing new ones (Alkire et al., 2008).

Also, military demands are driving calls for increased flying time to improve overwatch times. This need could form the basis for an aeronautics grand challenge—the development of a UAV that can stay aloft for very long periods of time (say, one month or one year).

Supersonic Business Jets

Another vehicle concept being explored in aeronautics circles is that of a supersonic business jet. Although research on sonic boom reduction and supersonic flight efficiency would also apply to military systems, data on the value of travel time indicate that supersonic business jets may remain a small niche unless the costs can be significantly reduced. Solving the sonic boom problem for overland flight is an additional challenge.

An interesting grand challenge, therefore, might be supersonic flight at subsonic prices. Such a challenge could allow the aeronautics research community to explore whether there are feasible, economically viable ways to fly supersonically (say, on very long flights). Of course, simple physics may preclude this unless major breakthroughs are achieved, but such a challenge is only one example of the advancement that might be necessary to enable significant commercial supersonic flight.

Large Vertical-Lift Vehicles

Another interesting area with both military and civilian applications involves vertical takeoff and landing and super-short takeoff and vertical landing (SSTOVL) vehicles. There continues to be a market for VTOL under special circumstances where airports are not practical or where transportation end points are not predictable. Applications include helicopters for police, fire, search and rescue, air ambulance, and the military. Research topics can include improved safety, fuel efficiency, and noise control.

More revolutionary concepts may also be a consideration. Research could pursue radically improving the capabilities of rotary-wing vehicles by increasing speed, range, payload capability, and propulsive efficiency. Applications could include large military rotorcraft providing point-to-point travel behind enemy lines (e.g., the so-called vertical envelopment concept¹¹) or civil use of such vehicles, operating from small airports in a metroplex concept. Both applications would require major research advances.

The vertical envelopment concept proposed by the U.S. Army has generally fallen victim to the relative immaturity of the field and its inability so far to provide the capabilities required. If these vehicles were based on current systems, their costs would prohibit acquisition in large numbers and would result in considerable unwillingness to expose such high-value vehicles to combat risks (Grossman et al., 2003).

The futuristic notion of employing vertical lift vehicles as part of the air transportation system to tie in small, regional airports would likely fall victim to the comparative efficiency, noise, and safety pitfalls facing current rotorcraft technology. But if rotorcraft could be made as safe, efficient, and quiet as fixed-wing aircraft through a grand challenge effort, then such vehicles might have a major role.

Air-Breathing Hypersonic Vehicles

Finally, let us briefly discuss the perennial question of the drivers of research on hypersonic vehicles.

The concept behind air-breathing hypersonic vehicles is to use atmospheric oxygen during flight in the atmosphere so that the vehicle does not need to carry its own oxygen for this stage, reducing weight and increasing payload. This is in contrast to rockets, which carry both oxygen and fuel for this stage of combustion.

¹¹ See, for example, Grossman et al. (2003) for a discussion of this concept and its technical and logistical challenges.

Two major applications are being considered for such vehicles if the concepts can be matured. First, air-breathing hypersonic engines could be used for space access, potentially reducing costs. Second, the military has envisioned hypersonic strike vehicles that use speed to penetrate air defenses. Space access is a current and continuing need. Hypersonic strike vehicles are future concepts that depend, in part, on whether they can be developed and on their costs and reliability relative to alternative approaches to global strike.

Although we did not conduct extensive analysis of the status of air-breathing hypersonic ramjet and scramjet engines, let alone other vehicle components, such as the thermal protection system and the overall system concepts being researched today, we do know that these efforts remain in the research phase. Thus, the conceptual drivers are there (at least for space access), but the actual drivers to proceed with a development program will likely hinge on the resulting parameters of viable concepts coming out of research.

Discussion

Although these types of vehicles were discussed at length during our brainstorming and debate within the project team, they nevertheless are illustrative rather than exhaustive. The key point here is that creative exploration of possible research drivers needs to be tempered by reality. What are the realistic drivers that might lead to a breakthrough? What are the technical realities? Is it worth some exploratory research of revolutionary concepts to look for major breakthroughs, or do market forces or technical realities make these ideas unrealistic?

A strategic review of research opportunities should consider both sides of this discussion explicitly. This will allow oversight of research decisions while allowing outsiders to understand the facts and considerations. Interested parties may not agree with the final decisions, but someone has to make them. Explicit discussion of the range of considerations and the basis for them must be made.

Fostering U.S. Competitiveness

The National Aeronautics R&D Policy (NSTC, 2006) cites U.S. competitiveness as an overarching driver of government investment in aeronautics R&D. Consider the following three ways to think about competitiveness and the role of the U.S. government in supporting research to promote competitiveness.

First, there continues to be a tradition of a broad governmental role in basic research funding across the sciences (such as that provided by the National Science Foundation and the National Institutes of Health).

Second, there is recognition that international competitors such as the Europeans are making governmental investments in R&D to improve their own competitiveness

relative to that of the United States. See, for example, the European Strategic Research Agenda (ACARE, 2004a, 2004b, 2008) and the European Commission's aeronautics vision for 2020 (Argüelles et al., 2001, p. 26).

Third, there is a governmental role in research related to national defense. This includes some trickle-down and some dual-use research topics, but, by policy, civil organizations such as NASA do not have a primary military mission (NSTC, 2006).

Each of these views provides a way to think about research drivers and what the government's role could or should be. In the first case, investments in basic science tend to be at a relatively low level when they are not motivated by specific social drivers of the type that we have been discussing. Thus, if NASA and other government research were for the general advancement of science, one would expect a relatively low level of basic research investments. However, given the drivers discussed, it is clear that there are some valid reasons why the United States should pursue more significant research *if* compelling and viable research opportunities exist that appear to have a definite cost/benefit or NPV payoff. For example, it could be that some concepts are simply too expensive to pursue in some areas, so a determination needs to be made concerning the viability of these concepts relative to the total investments needed.

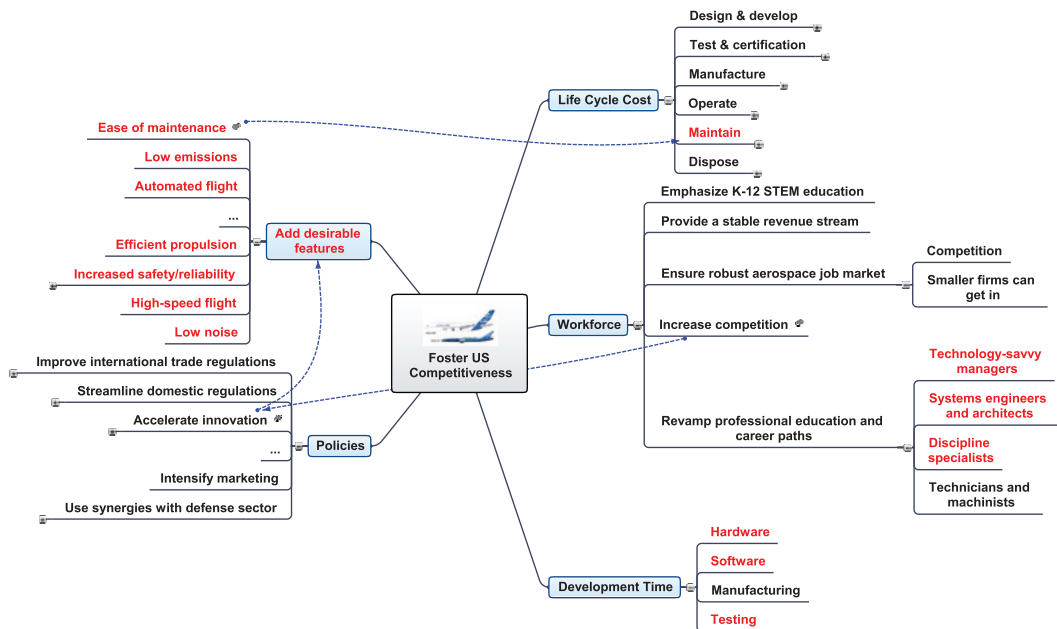
Second, international competition can be a compelling motivator of U.S. research investments, but, again, we need to know if the research opportunities are viable and if the payoffs are appropriate. In some technical areas, manufactured components have become commodities or the profit margins have been driven so low by competition and available production capacity that U.S. companies have exited in favor of other investment opportunities. Here, the argument has been made that the United States should focus on high-end manufacturing to leverage its generally highly skilled and well-educated workforce. One should also note that the competitive landscape is also evolving as a result of increased regulatory restrictions on noise and emissions, for example. These areas may indeed keep aeronautics production (or portions of it, at least) from becoming mere commodities because advances in engines, aeronautic design, and systems design and integration appear to require real advancement in technology (not simply efficient production of similar components).

Third, U.S. national defense continues to rely on advancing technological capabilities. Some of these have been in the aeronautics field, but the long-term trend over the coming decades is not clear. Current advances in UAVs have given the United States significant advantages in ISR and loitering strike capabilities, but other areas, such as high-end fighters like the F-22A and F-34, have no significant peer competitors. There is always the concern that other countries will continue to improve their fighter and bomber capabilities over time, driving a U.S. need for improved next-generation capabilities, but current emphasis on irregular warfare has driven the demands toward unmanned aircraft capabilities. In all these areas, the question remains, what roles should the government play to maintain U.S. national security

competitiveness outside DoD activities? Here, dual-use areas, such as supersonic boom quieting and the use of UAVs in civil air space, remain significant considerations.

Figure A.9 provides an example decomposition of areas that relate to fostering U.S. competitiveness. Using our expert judgment of the challenge and our decomposition of the basic options available, we highlight areas in red where aeronautics research could have a significant contribution. Most research opportunities lie in the area of adding desirable features and capabilities to the systems (i.e., along the lines of the drivers discussions above) plus some consideration of new ways to reduce development time and of how we could improve our workforce intellectual capability. Note, in contrast, that such areas as reducing life-cycle costs may be more the responsibility of industry than of foundational research, except possibly for research into ease of maintenance.

Figure A.9
Conceptual Option Decomposition for Fostering U.S. Competitiveness



Research Themes Decompositions and Conceptual Approaches

Strategic analysis based on policy, drivers, and vision provides only part of the information needed to make research investments. Even if there is an exceptional need in an area, decisionmakers also need to understand if there are viable technological ideas and concepts worth investing in. Such technical assessments ask which concepts are viable and address broader issues related to cost and implementation barriers.

In this appendix, we illustrate the decomposition of individual research themes into their fundamental elements to enable a high-level discussion of technical approaches and viability. Our objective is to outline fundamentals and provide a broad picture of the possible. The aim is not to provide exhaustive decompositions but to illustrate the concept of decomposition itself and provide reasonable examples. These examples could form the basis for further analysis and elaboration by domain experts as well as validation of novel ideas under consideration.

Problem Decomposition

Before we get into specific examples, we first discuss the decomposition process generally. In decomposing each problem area into technical options, we need to explain the fundamental ways in which a problem can be addressed. This allows one to explain the basic challenges, the approaches taken (and not taken), and why. In this way, we can identify the paths taken and whether (and when) we should reconsider those paths, and we can explain to stakeholders how we arrived at our decisions and the basis for those decisions.

We also need to explain how aeronautics R&D fits into solving the problems; the roles of other players, such as industry; the current and future regulatory environment; operational paradigms and doctrine; the marketplace; infrastructure drivers and barriers; etc.

Consider, for example, a notional grand challenge of tripling passenger air transport system throughput. Table B.1 shows a partial decomposition of a purely notional challenge into fundamental approaches that could be taken (separately or together), along with decomposition of subproblems and subapproaches. Note that

Table B.1
Partial Decomposition of a Notional Grand Challenge

1. Triple passenger air transport system throughput
1.1 Reduce air traffic congestion at airports
1.11 Enable planes to fly closer to each other with minimal distances
1.111 Allow planes to fly in formation safely
1.1111 Set up automated data links between different airlines and the controllers
1.1112 Set up sensors that provide real-time monitoring of distances between planes feeding the information to an adaptive control system that stabilizes the plane while flying in formation
1.112 Reduce/eliminate wake behind aircraft
1.12 Maximize airspace using VTOL (including tilt rotors)
1.13 Develop port designs that enable landing planes on water, air, and land
1.14 Optimize landing and takeoff protocol in a multiport city
1.2 Increase capacity of aircraft to X
1.3 Increase speed of aircraft to Y

we are not arguing for this as a viable grand challenge per se; rather, we use this as an example to illustrate the decomposition process.

Here, we take each problem or challenge and outline options to consider for meeting that challenge. This is continued in an iterative, recursive fashion to break down the problem into future steps until we arrive at goals and objectives that are more amenable for technical examination.

Note that this kind of linear format for problem decomposition quickly becomes hard to read and makes it difficult to represent positive and negative correlations between subareas. It is also not clear from a simple listing whether each subordinate objective is required to meet the current objective, or whether each is a separable option (i.e., is this an “AND” list or an “OR” list). Therefore, when the decompositions become more complex, we employ a chart decomposition approach below when breaking down each area into logical components and the range of possible approaches that could be pursued to achieve each goal.

UAVs in Civil Airspace

Issues in flying UAVs in civil air space generally include the following:

- Collision avoidance. Special procedures are needed to reduce the risks of midair collisions resulting from less precise altimeters and other sensors, modest lag time in remote control, limitations in seeing and avoiding other aircraft (Government Accountability Office [GAO], 2008), and the possibility of intermittent or lost control of UAVs from ground control stations. For example, the Defense Science Board (DSB) stated that “Conflict avoidance, especially in a fully autonomous, lost-link situation will be the ‘Achilles Heel’ challenge for the FAA to approve” (DSB, 2004).

- Security protection. Unmanned systems in general do not have the same level of security protection in terms of communications and physical security (GAO, 2008).
- Reliability of UAV vehicles and systems. UAVs and supporting systems are relatively immature, and their failure rates are higher than those for commercial systems (CRS, 2006). This includes a recognized need to improve human factors in UAS (GAO, 2008).
- Need to update airspace regulations. The lack of a regulatory framework has limited the inclusion of UAVs in civil airspace. Flights are currently allowed on a labor-intensive, case-by-case basis (GAO, 2008).
- Privacy concerns. The widespread use of low-flying UAVs has also raised privacy concerns because of their surveillance ability.

Some of these areas involve technical issues, such as the reliability and security of UAVs and associated systems; others involve issues outside aeronautics research, such as regulatory, privacy, and physical security issues.

2x-3x Airspace Throughput

Various approaches could be taken to increase airspace throughput. First, airspace capacity itself could be increased to allow a greater number of flights. Second, aircraft size could be increased to allow movement of more goods and persons in the same number of flights (probably with some modest adjustments in aircraft spacing during takeoffs and landings). Third, airport capacity could be increased either by improving existing airports or increasing the number and use of alternative airports. Finally, additional time-shifting could be pursued to level airport demand at peak times, but market forces will likely dictate the viability of this option.

FAA and NASA research on airspace throughput has focused on aspects of the first and third areas as follows. Below is a high-level sampling of some of the research topics being pursued. However, we did not conduct an in-depth analysis of the status of NextGen or the approaches employed. It is also not clear if research on efficient, large aircraft could be a new, viable research thrust and how that approach would rank against existing research thrusts.

NextGen air traffic management research has focused on many approaches to improve airspace capacity. These include using advanced technology, such as trajectory-based air-traffic management, dynamic configuration of the airspace, predicting flight trajectories, improving flow management, improving and assuring separation, processes and decision support to facilitate super-dense operations, as well as tools for designing and simulating air traffic and its management. Optimizing operations for takeoff, departure, approach, and landing may provide the opportunity for

increasing airport throughput. Using better tools to help track flights may allow air traffic controllers to track more flights without adding to their workload or detracting from their ability to perform their important tasks.

Air portal research has focused on ways to improve surface operations and better manage arrival and departure schedules, as well as on transition and integration management by simply adding runways, dynamically managing aircraft spacing on take-offs and landings, and research to reduce wake turbulence to reduce spacing requirements. Research plans also discuss the concept of employing rotorcraft and personal air vehicles in the long term to integrate the use of regional airports into the commercial air travel system.

2x-3x: Efficient Large Aircraft

Increasing aircraft size to achieve more airport throughput is an option that would not require changing airport operations as long as the airport can handle vehicles of the size in question. This option requires only that airlines use a larger aircraft for a flight. For example, instead of flying four daily flights from airport A to airport B using a 50-passenger Embraer ERJ 145 or Bombardier CRJ200, an airline could instead fly four daily flights from airport A to airport B using a 150-passenger Boeing 737 or Airbus A320. Without changing the number of flights in the air between airports A and B, this would triple the throughput.

Green Aircraft

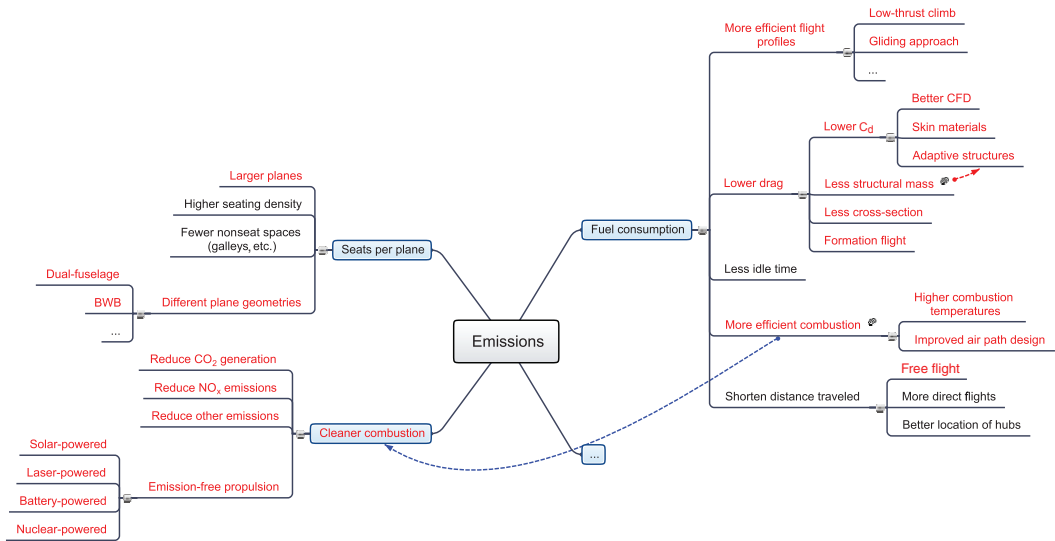
A “green aircraft” research theme would combine goals across environmental issues to focus on the more important aspects while trying to keep less important factors low or minimize their growth.

Figure B.1 shows a breakdown of the fundamental approaches for reducing emissions. The top-level areas include improvements in fuel consumption (i.e., efficiency in vehicles or engines), cleaner combustion (where fewer offending chemicals are emitted), and new vehicle concepts that can improve the passenger capacity of aircraft to result in reduced emissions per passenger mile.

N+2 and N+3 Aircraft

Generally, technical approaches include component improvements, aircraft-wide system integration improvements (i.e., positioning of engines to reduce noise and improve performance), new aircraft shapes and configurations (e.g., the advancement of current “tube-and-wing” aircraft (called N and N+1 in NASA parlance), new blended-wing body concepts (N+2), and the search for other new concepts (N+3).

Figure B.1
Preliminary Breakdown Maps Outline Key Components for Fuel Efficiency and Reduced CO₂



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Reduced CO₂

As indicated in the discussion in Appendix A, CO₂ reductions appear to be the most important chemical emission need for aeronautics based on total volume and emissions per passenger mile.

Reductions in CO₂ emissions could be addressed by research to increase the efficiency of engines and vehicle types. Examples of the former include revolutionary engine concepts, such as variable pitch turbine blades, where pitch is optimized for each operating condition. Examples of the latter include such candidates as the blended-wing body or hybrid-wing body (HWB), for which early indications demonstrate operating efficiencies, as well as the search for new vehicle concepts in the “N+3” program at NASA.

CO₂ reductions might also be achieved through the use of alternative fuels that produce lower carbon or no carbon. Conversely, the use of hydrogen would produce no CO₂, but there are practical challenges to its use in aircraft compared to use of current carbon-based fuels. Table B.2 shows the density, specific energy, and energy density of common carbon-based fuels and hydrogen fuels. Current aircraft fuels (Jet-A and Jet-A1) are basically kerosene (along with some additives and extra quality control). The specific energy (energy per unit weight) is lower for kerosene than for hydrogen, but the energy density (energy per unit volume) is higher for kerosene than for hydrogen. In other words, hydrogen brings a lot of energy by weight (almost three times as much), but it unfortunately takes a lot more space than kerosene (about four times more).

Table B.2
Heats of Combustion for Candidate Alternative Aviation Fuels

	Specific energy (MJ kg ⁻¹)	Energy density (103 MJ m ⁻³)	Density (kg m ⁻³)
Kerosene (typical): jet fuel	43.2	33.8	783
Methane (liquid)	50.0	21.0	421
Ethanol	21.8	17.1	785
Methanol	19.6	15.4	786
Hydrogen (liquid)	119.7	8.4	70

SOURCE: Penner et al., Section 7.8, 1999.

Thus, a hydrogen-powered aircraft would need to store about 33 percent more fuel than a similar aircraft powered by kerosene.

Reduced Fuel Consumption

Fuel efficiency can involve a number of fundamental research approaches, including lower drag, more efficient fuel combustion and engine operation, and more efficient flight profiles (see Figure B.1). Other nonresearch areas include, for example, operational efficiencies, where idle time is reduced and total flight time is reduced per trip (e.g., through more direct flights). Examples of concepts for improving drag include super-efficient cruise technologies, such as active or structural boundary-layer control, plasma flow manipulation, and improved engine-airframe integration and configurations. Examples of improved engine concepts include variable bypass ratios, adaptive turbine glade pitches, and tradeoffs between noise and fuel efficiencies in flight.

Reduced Noise

Various approaches are taken to reduce the noise output of aircraft. Aircraft noise continues to drive airport authorities across the country to maintain specific landing and takeoff routes to avoid violating residential area noise rules.

Aircraft noise has been reduced through the years using more advanced engine technology. Reductions in noise emissions involve some of the same factors as in fuel efficiency (e.g., reduced drag, system studies for improved engine location, and engine efficiency). Engine research continues into ultra-high bypass ratio engines, which may also reduce aircraft noise further. An interesting research area that is not attracting much attention from the commercial and civilian aircraft sectors is the concept of variable bypass ratio engines. These engines have been of interest to the military because of their drastically increased fuel efficiency (greater than 25 percent) but they should have similar benefits to the commercial civilian sector.

In addition, recent research on aircraft designs such as BWB aircraft, originally pursued to improve fuel efficiency, also produced some noise reduction benefits.

Efficient Tradeoffs

The latest-generation aircraft advertise more fuel efficiency, but the story is actually more complicated than that. Figure B.2 plots the fuel efficiency of sample aircraft in terms of passenger miles per gallon. Here, we notice that the new Airbus A380-800 offers a slightly higher passenger mile per gallon with one-class seating than the older Boeing 737-800 aircraft. The reason is that fuel efficiency is but one performance measure and can be traded for other measures such as flight range. Furthermore, it is important to note that in addition to carrying passengers, all aircraft carry cargo. Large aircraft such as the A380, 747, and 777 carry large amounts of cargo in each flight, a capacity that is not reflected in Figures B.2 and B.3.

Figure B.3 plots passenger miles per gallon versus aircraft range. Here, the aircraft passenger miles per gallon does show improvements over time. The Boeing 747, 777, and 787 show fuel efficiency improvements in addition to range improvements. Thus, it is important to remember that fuel efficiency is convolved with other factors (such as range) that need to be considered when setting efficiency objectives.

Figure B.2
Fuel Efficiency, by Initial Year of Sample Aircraft (passenger miles per gallon)

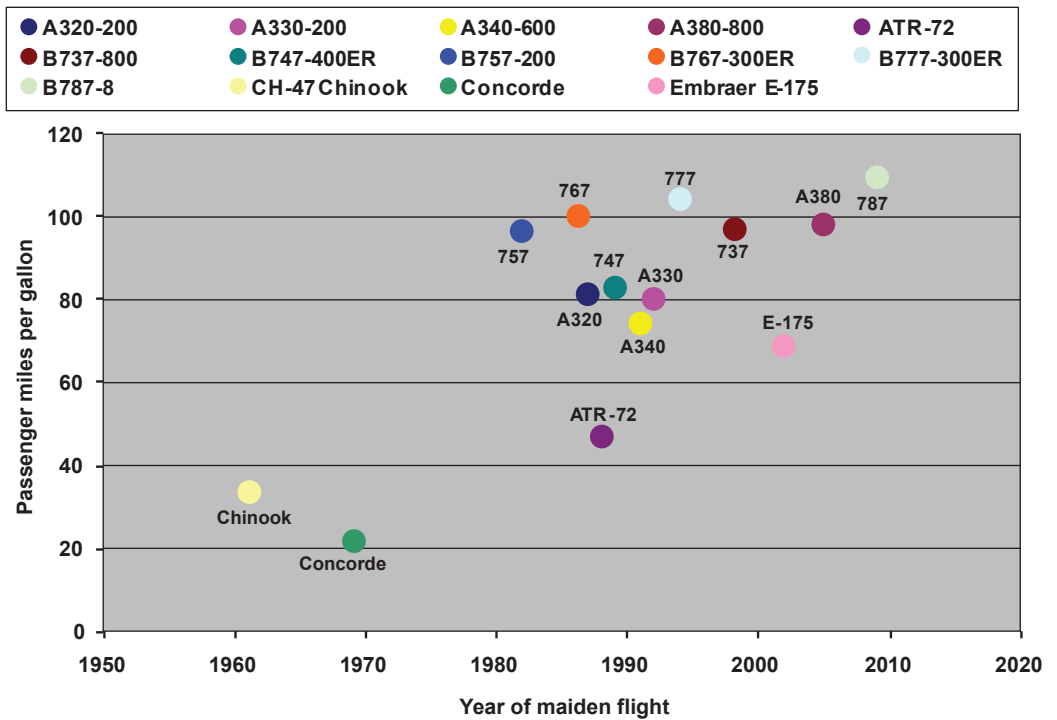
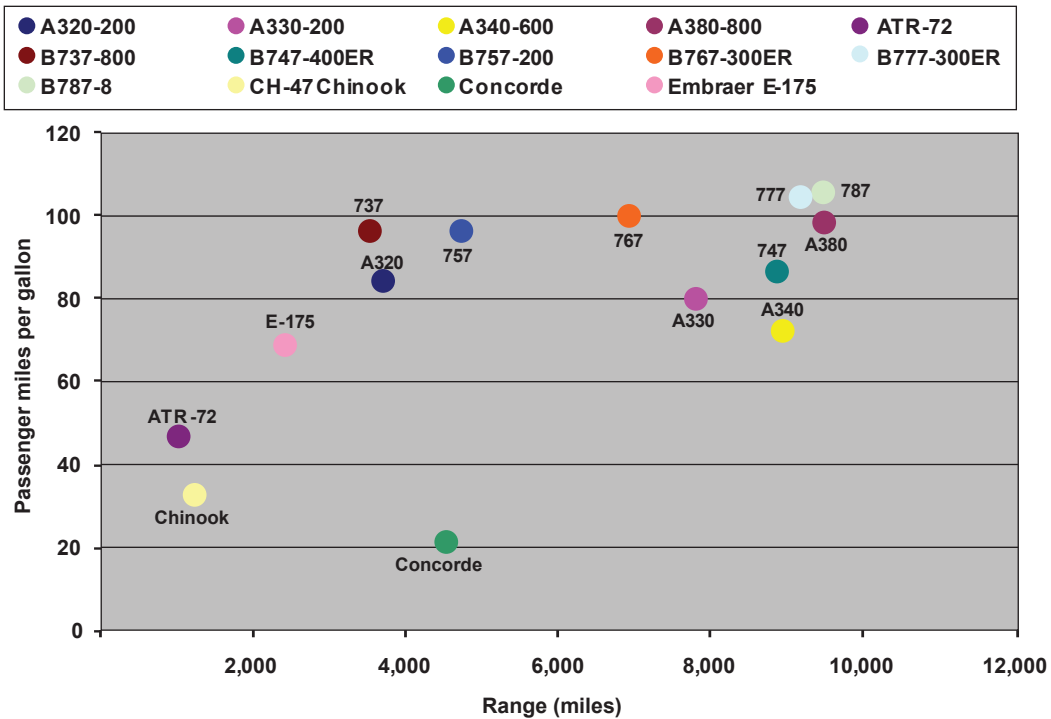


Figure B.3
Fuel Efficiency, by Range of Sample Aircraft (passenger miles per gallon)



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STOVL/VTOL Large Transport (Wide-Scale Civil Airspace Rotorcraft and Vertical Envelopment)

The R&D of advanced or revolutionary STOVL and VTOL vehicles could be a different kind of research thrust to consider. The development of practical and more economical vehicles of this type could enable civil and military concepts, such as the wide-scale use of such vehicles in civil airspace to incorporate more rural airports in the broader national airspace system as well as futuristic Army concepts such as vertical envelopment.¹ Both of these concepts are currently challenged by the practical issues of cost, efficiency, noise, reliability, and performance of current rotorcraft and STOVL vehicles.

¹ Vertical envelopment is a “tactical maneuver in which troops, either air-dropped or air-landed, attack the rear and flanks of a force, in effect cutting off or encircling the force” (DoD, 2010). See, for example, Grossman et al. (2003) for a discussion of this concept and its technical and logistical challenges.

Research candidates in this area include concepts that attack one or more of these challenges: reduced and variable rotor speeds, improved rotor efficiency, increased payload concepts (e.g., to 25 tons or more), tilt-rotor versus multirotor helicopter trade studies, and reliability/safety management during lift failure.

General Aviation Airplane Safety

Although the costs and fatality rates for general aviation warrant consideration of general aviation safety as an important research topic, are there viable technical approaches that could be considered to address this challenge? A research theme on improving general aviation safety could address the challenges of obstacle detection, collision avoidance, improved automated health maintenance and failure detection, and emergency response and mitigation (hopefully while maintaining or reducing noise and emissions).

In our review, we found some interesting potential technical approaches to a grand challenge in general aviation. Conceptually, we can decompose general aviation safety into five major factor areas: increasing aircraft reliability, reducing sensitivity to human errors, improving crash procedures, increasing survivability after a failure or crash, and emphasizing a safety mindset throughout. Figure B.4 provides a graphical decomposition of these five areas into subordinate considerations. We identify in red the areas that seem to have major aeronautics research aspects from this kind of fundamental decomposition, but of course other areas have challenges, and new research ideas may come forth from those areas as well.

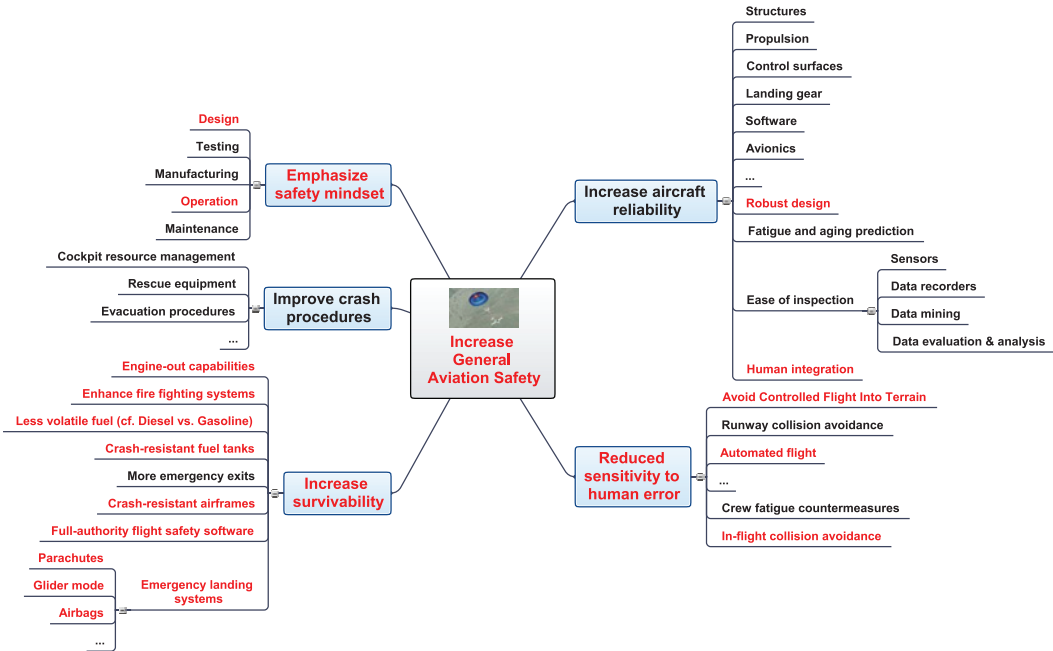
Fatality Drivers

A different way to approach the general aviation safety question is to ask, what are the primary sources of fatalities? Four major fatality drivers for general aviation were identified by a review paper by Li and Baker (2007): fire, weather, off-airport landing, and failure to use safety restraints.

For fire, the goal would be to reduce the frequency and consequences of such incidents. Approaches include enhanced engine and fuel technologies that reduce the risks of fires in the first place, improved structural measures (e.g., fuel tanks and fuselage firewalls) to reduce the spread of fire, and the addition of active fire suppression systems.

For operation in adverse weather, technologies could be introduced to reduce pilot error (e.g., training or providing real-time advice on proper procedures during icing) as well as technology to improve the robustness of the vehicles themselves in such conditions.

Figure B.4
Conceptual Option Decomposition for Increasing General Aviation Safety



NOTE: Areas in red are of particular importance to aeronautics research.

RAND MG997-B.4

For off-airport (emergency) landing, R&D into integrated emergency systems could be explored. This includes such concepts as airframe parachutes (see Figure B.5), airbags, and automated landing systems for situations where the pilot is incapacitated, vision is poor, or vehicle components, such as engines or flaps, are inoperative. Examples include concepts by Cirrus Aircraft (undated) and Rockwell Collins). The “digital parachute” concept by Rockwell Collins (2009) employs an automated landing capability that uses current technology for landing commercial vehicles in such adverse weather as fog (Rockwell Collins, 2008).

Finally, for failures to use safety restraints, better pilot and passenger training as well as safety interlocks, such as those used in automobiles, could be researched and employed.

Research to prevent and mitigate pilot error could help across all four fatality sources. Pilots could benefit from improved situational awareness through better instruments and decision support, improved collision avoidance and emergency response and control, and a focus on collision avoidance (see, for example, advanced cockpit concepts by Cirrus shown in Figure B.6). Automation, such as more advanced auto-pilots and flight planning, could help pilots and their control of the vehicle. Furthermore, improved training can increase pilot awareness and capabilities in emergency situations.

Figure B.5
General Aviation Parachutes Concept



SOURCE: Cirrus Aircraft. Used with permission.

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Figure B.6
Improved General Aviation Cockpits and Human Interfaces



SOURCE: Cirrus Aircraft. Used with permission.

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Research Considerations

In considering this research theme, the government will need to assess which areas warrant government research and which are industry development and implementation problems. For example, what research questions remain that could improve on the kinds of concepts discussed by Rockwell Collins and Cirrus? Nevertheless, general aviation aircraft tend to include lower-cost vehicles and thus owners and manufacturers have fewer resources to spend on safety features and capabilities. This is probably aggravated by reduced regulator oversight and demands compared to traditional commercial air travel.

Also, we need to realize that the general aviation sector involves a diverse set of vehicle types. Table B.3 lists the general types of aircraft in use along with the number of vehicles in the general aviation and commercial air categories. Thus, although commercial air vehicles are mainly turbojet aircraft, general aviation’s are generally piston-driven aircraft but with large numbers of other types of vehicles with lower performance capabilities and safety margins. Thus, solving the general aviation safety problem may involve a number of different challenges rather than a homogeneous set of solutions.

Table B.3
Active Air Carrier and General Aviation Fleet in 2005

	Commercial Air	General Aviation
Turbojet	6,839	9,823
Turboprop	889	7,942
Piston	454	167,608
Helicopter	43	8,728
Glider	—	2,074
Lighter-than-air	—	4,380
Experimental	—	23,627
Total	8,225	224,182

SOURCE: BTS (2010b), Table 1-13.
NOTE: 2005 is the latest year available for data on air carrier and general aviation fleets.

Maintain Commercial Aviation Safety Levels

As mentioned, commercial aviation safety levels are very low compared to other forms of transportation. Still, changes in vehicle construction and design—as well as changes in air traffic control to improve throughput—could endanger this achievement. For example, new aircraft are made with more composite (rather than aluminum) components. Composite structures tend to fail catastrophically and have different failure

modes and reparability than metal structures do. Thus, a research theme on maintaining (not improving) commercial aviation safety levels could be a reasonable research topic.

Fundamental research approaches include composite structures that are “safe to fail” (e.g., damage-tolerant advanced stitched composites [Li and Velicki, 2008]), non-invasive condition-monitoring and inspection to detect impending failures, and maintenance data assessment systems for pilot and maintenance crews.

Aviation Security

Although aviation security is a key area in the national aeronautics R&D plan (NSTC, 2007, 2008, 2010), conceptual analysis shows that there are few aeronautic research opportunities for NASA for improving security. Figure B.7 shows a conceptual decomposition of the major areas of aviation security. NASA and other research opportunities (shown in red) are primarily in the aircraft component. These include the detection of chemical, biological, radiological, nuclear, and explosives (CBRNE) threats in cargo or the cabin; remote automated flight control takeover in the case of a hijacking (and prevention of others from usurping such as capability); and countermeasures for man-portable air-defense systems (MANPADS)² that could be launched by terrorists or other adversaries wanting to take down an aircraft. Much of the remaining areas are the responsibility of the Transportation Security Administration and airport security procedures rather than fundamental aeronautics research per se.

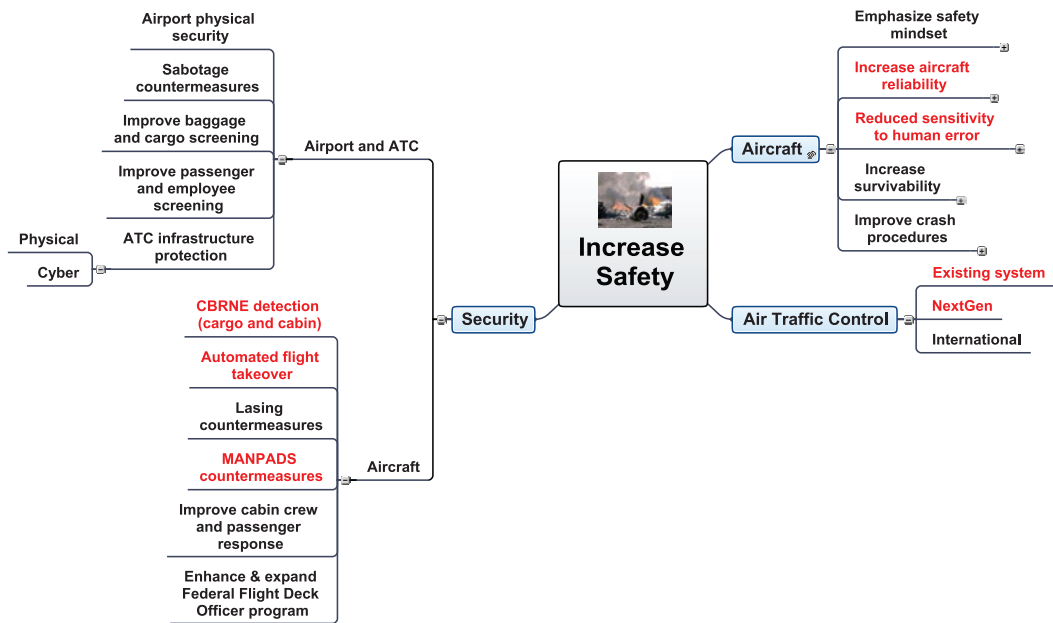
Supersonic Flight over Land at Transonic Prices

The question of whether supersonic overland flight is technical and economically feasible provides interesting technical challenges. Our social analysis presented in Appendix A showed that having a large market would likely hinge on a development that had very little marginal increases in cost over current transonic flight (below the sound barrier). As a result, the major technical challenges include a significant mitigation of the sonic boom problem and efficiency. Public outcries over noise mandate the former and market economics the latter.

The question, then, is one of physics and technological realities. Is it really possible to develop such flight (say, for very long distance flights where the penalties in accelerating to supersonic speeds can be spread over longer distances), or is such a revolutionary concept not realistic?

² MANPADS are usually shoulder-launched surface-to-air missiles (DoD, 2010).

Figure B.7
Conceptual Option Decomposition for Improving Aviation Security



NOTE: NASA and other research opportunities are shown in red.

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If it is not realistic, then research on sonic boom mitigation can have useful military applications, which will likely retain supersonic capabilities, but commercial supersonic flight will likely remain a small niche.

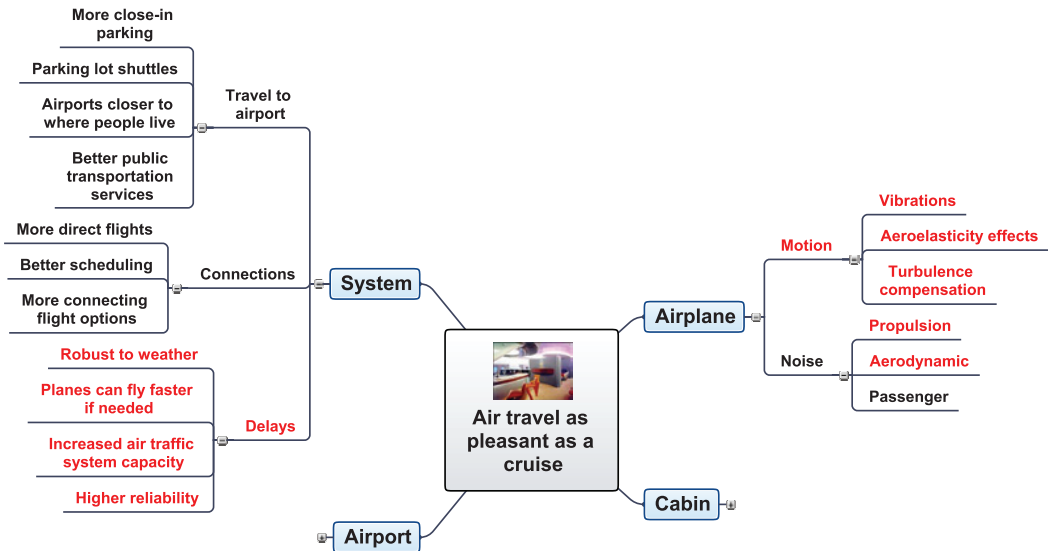
Increased Air Travel Flexibility and Comfort

We now examine available information related to air travel flexibility and comfort.

Other Than Delay, Most Issues Related to Comfort Are Industry-Driven

A common complaint from those who travel (or at least from the authors!) is that air travel is not enjoyable. We therefore considered how aeronautics research might make air travel not unpleasant. However, our conceptual analysis determined that most areas related to air travel comfort and convenience are market-driven rather than research-driven. Figures B.8 and B.9 show key factors in this decomposition and supporting aspects related to comfort. We assessed airport and cabin comfort to be largely driven by market forces (see Figure B.9). That is, air travel could be made more convenient for higher ticket prices, but market forces seem to focus more on lower prices than increased comfort. Consider, for example, the relative use of business class versus economy class.

Figure B.8
Conceptual Option Decomposition for Increasing Air Travel Comfort: Air System and Airplane



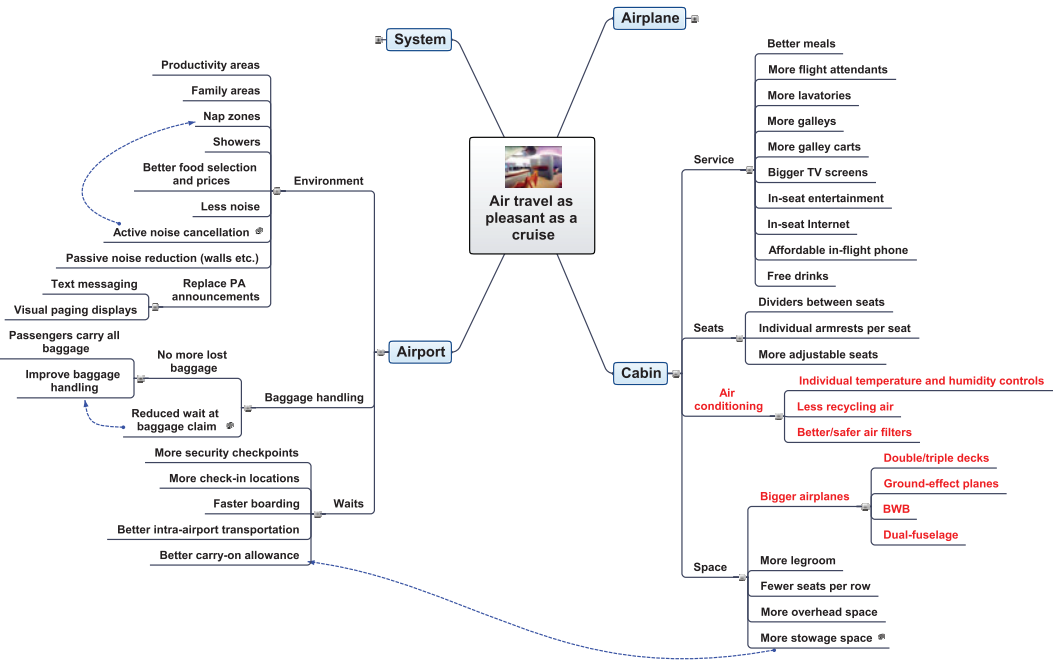
RAND MG997-B.8

Some areas of airplane comfort related to motion and noise could be improved through aeronautics research (see the areas in red on the right side of Figure B.8), but these areas do not appear to be the basis of passenger complaints.

At the aviation system level, there are also some possible improvements, but many are not aeronautics-driven. Delays are the largest area where aeronautics might yield improvements but, as we mentioned above, the major factors of delay are related to airspace congestion in certain areas and issues related to weather. Other factors, such as shorter flight times (i.e., flying faster), are not supported by the marginal economic value of reduced flight time.

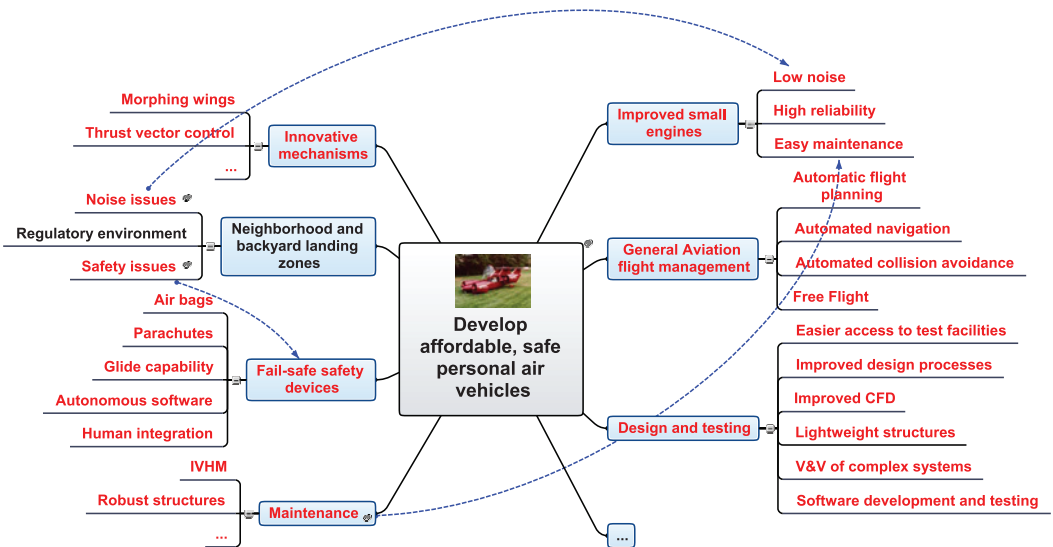
Revolutionary flight concepts such as so-called personal air vehicles (PAVs) might be a more direct way for aeronautics research to improve air travel convenience and comfort, but it is not clear whether these notions are commercially viable. Current general aviation planes are much too expensive for the general population as a whole. Figure B.10 shows a conceptual decomposition of PAV research areas. NASA did perform some research into PAVs in the early 2000s (NASA, 2001) and some in NASA still discuss these ideas, but there appears to be a lack of momentum and integrated planning to pursue such concepts and tie them to commercial recipients.

Figure B.9
Conceptual Option Decomposition for Increasing Air Travel Comfort: Airport and Cabin



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Figure B.10
Conceptual Option Decomposition for Personal Air Vehicles



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Air-Breathing Hypersonic Missiles and Space Access

The concept of air-breathing hypersonics (where the use of atmospheric oxygen reduces the need to carry oxygen in the vehicle) hinges on two major areas: hypersonic engine development and hypersonic airframe design and thermal protection. Both areas present significant research challenges to pursuing a viable and cost-effective air-breathing hypersonic vehicle.

Air-breathing hypersonic engine developments employ ramjet and scramjet concepts at supersonic and hypersonic speeds. Although such engines can operate in a sustained condition, technical challenges remain, including materials and injection technology for scramjet engines and efficient alternative means for accelerating to the optimum speeds for scramjet operation.

Hypersonic airframe design challenges include the difficulty of studying air-flow transition under hypersonic speeds, evaluating control surface options, developing long-lived thermal protection systems, and developing appropriate and affordable ground and flight test facilities and capabilities.

Positive and Negative Synergies Between Aeronautics Research Objectives and Concepts

As we have observed in some cases already, there are positive and negative synergies between some technical approaches to addressing the aeronautics research drivers, goals, and objectives discussed above. It is important to recognize both the potential for such synergies and to look for them when planning and selecting research paths. Some are more obvious (such as the ones highlighted below), and others will be uncovered during the course of research and may not be knowable a priori.

Positive Synergies

Below are examples of positive synergies between research themes and approaches.

Automated flight management can facilitate increased safety (if reliability is improved while avoiding problems such as collisions), improve national security (e.g., by enabling the use of UAVs in civil airspace), and help to improve comfort, convenience, and U.S. competitiveness (e.g., by improving flight operations, reducing delays, and enabling such concepts as regional airport integration and personal air vehicles).

Fuel efficiency objectives can help meet emission objectives (e.g., by reducing CO₂ emissions). More efficient combustion might also result in cleaner combustion with fewer other chemical and particulate emissions. More efficient engines might also result in reduced life-cycle costs if they prove more reliable or reduce internal contaminants.

Reducing noise emissions can facilitate an increase in national airspace capacity (e.g., by improving the throughput of existing airports, increasing the flight pat-

tern zones around airports, and allowing the creation of new commercial airports). Reduced noise could also improve passenger comfort and, in turn, improve the competitiveness of companies producing quieter aircraft on the national and international markets (both for passenger and regulatory reasons).

Increased U.S. competitiveness could in turn facilitate R&D investments in other areas, promote innovation, and enable development, production, and use of progressive advances.

Negative Synergies

Identifying negative synergies is important to make sure that progress in one area is not made at the expense of progress in other areas. The existence of such synergies also implies that prioritization of goals is important to allow researchers to make useful tradeoffs that might otherwise be discarded despite their value. Below are some examples of potential negative synergies.

The expanded use of personal air vehicles (say, with the objective of improving throughput, comfort, convenience, and competitiveness) could result in a significant increase in flight volume with resulting challenges to efforts to expand airspace capacity. Also, if personal air vehicles turn out to be less efficient than more expensive vehicles, overall noise and emissions from aviation might be increased. In addition, some types of personal air vehicles might be less safe as a result of fundamental designs, vehicle types (e.g., rotorcraft and other general aviation vehicles have a poorer safety record than commercial jets), quality and testing of parts, performance in adverse conditions, or less regulatory oversight.

Efforts to improve the comfort and convenience of aircraft may conflict with systems or procedures for improved security (e.g., current delays at airport screening lines), might increase emission and fuel consumption (e.g., if rotorcraft are used increasingly without bringing their emissions in line with other vehicle types), and could increase demands on the national air space (e.g., by use of more, smaller aircraft from more airports to enable more direct travel to airports closer to final destinations).

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